International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 11, No.1 (Jan-2022)

http://dx.doi.org/10.12785/ijcds/110158

# Minimum Order Quasi-Decentralized Functional Observer (MOQDFO) for Frequency Regulation in Multi-area Power System with DC Link and TCPS

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*Received 31 Dec. 2020, Revised 3 Jun. 2021, Accepted 31 Dec. 2021, Published 31 Jan. 2022*

**Abstract:** Here, the novel minimum order quasi-decentralized fractional observer is proposed for frequency regulation in a multi-area power system with DC Link and thyristor controlled phase shifter (TCPS) integrated with battery energy storage system (BESS). While it is difficult to estimate the states of large multi-area power system, a quasi-decentralized observer controller is designed of single order with linear functional control approach and thus estimated control signal is directly utilized in each area. System performance is investigated in respect of frequency regulation vis-à-vis step and random load changes in any one area with and without AC/DC Link and TCPS coupled in the system. Results are compared and contrasted against the existing state feedback optimal controller and observer based controllers and the analysis is presented thereof. The results obtained are almost mimicking the results of state feedback optimal controller with the system dynamic performance showing improvement in respect of peak overshoot and settling time. The simulations are executed in MATLAB$^{(R)}$.

**Keywords:** Frequency Regulation, TCPS, DC Llink, Linear Functional Observer (LFO), Power System

## 1. INTRODUCTION

The world in recent times is witnessing a rise in the use of distributed generation (DG) sources and consequently the complexity of power grid is also increasing due to one of many reasons of integration of DGs into the conventional power system. Many strategies have been developed in the past for load frequency control (LFC) in a multi-area power system with conventional generators. In LFC, the frequency is regulated vis-à-vis the load variations meaning thereby the balance is maintained between power generation and consumption using suitable control strategy. There are many researchers who have worked on LFC and reported their novel control strategies [1][2][3]. Due to extension of power system and development of modern control strategies, we need to re-emphasize different control methods in power system with integration of different generating sources. LFC gains high attention with integration of various sources for instance, LFC with integration of wind energy is reported in [4][5]. Proportional-integral (PI) control has been the most popular conventional control method for LFC in large interconnected power system and further, with the development of state variable approach of modern control theory, the optimal state feedback controller, which has been discussed in many research works. Optimal control with full state feedback is one of the most optimal methods till now however, the limitation of non-availability of all states and cost limitation of using measuring devices for each state has motivated the research towards estimator/observer. Optimal control is put forth in [2][6][7] for hybrid power system comprising conventional and renewable sources. To overcome the non-availability and distortion of available state vectors, observers/estimators have been considered by many researchers while designing controllers but, these were of very high order. First time, the LFO was reported by Luenberger [8] in 1966 and subsequently the minimum order of functional observer was defined by Moore et al. [9] in 1975 and a bit modified by Furuta et al. [10] in 1977, which was considered of lowest order and a very significant development at that time and the same has been widely used in LFC studies for the last many

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decades but, it was not of as low order as it was considered to be. Further development is discussed under section 2.

With the expansion of power system geographically, it's not easy to transport or communicate all vectors for long distances and with the system expanding, the more appropriate and suitable approach would be to design decentralized/distributed observer controller. In the recent few years, this problem has been reported and seeking more attention to design individual controller for each area [11] [12] [13] [14].

In this paper, first section includes observer and its history whereas, second section explains the design of LFO and of the proposed observer (MOQDFO). Section third describes modeling of the system considered for the case study of the proposed controller, while in section four, the results are presented and analyzed with section five giving the conclusions.

## 2. OBSERVER'S EVOLUTION AND DEVELOPMENT

Observer is said to be a concept through which state vectors can be reconstructed via available input and output and it mimics the behavior of original system. State estimation, majorly contributed by Kalman in 1960s, has wide applications in control system problems, space trajectory, unmanned vehicles etc. Further, major contribution in deterministic system was made by D.G Luenberger who contributed major results towards full order observer, reduced order observer and functional observers, which gave satisfactory results towards noisy measurements and unknown noisy disturbance inputs [15].

It is always desirable to design observer with faster dynamic elements than the system which it observes. Major problem with observer was its high order. In Luenberger 's observer, a system having order N would have order 2N with observer which got reduced with systemic solving methods in further research [16][17][18]. A simple method to design functional observer of minimum order in direct correspondence with the number of functions defined is derived in [16]. Design algorithm for general case and existence condition of functional observer of minimum order is described in [17] for controllable as well unstablizable systems. This general algorithm has also been justified by the authors for all previous observers too by taking up specific examples.

Authors in [18] presented a novel technical note on the concept of observability and existence condition of minimum order observer and solution to design minimum order LFO even in conditions where the observer as proposed in [16] fails.

If the state observer is so designed as to be capable of estimating all states of the system irrespective of available state vector, it is known as full order observer and is very simple in design. Reduced order observers are designed to estimate only non-available output and have (n-p) dynamic order for a system of $n^{th}$ order with p available outputs [15][17]. Functional observer, being specific type of state observer, has contributed significantly towards reduction of order of a large system, which initially was introduced by Luenberger, with systematic design approach and existence condition given by Darouach M. [16]. This was big interconnected power system. Minimum order linear functional observer reported in [18] can solve the problem of order reduction in practical integrated power system which is of very high order. Centralized controller may face problem of communication delay and not only that, the noise available in inputs may also get transferred from other areas in large interconnected power system. To overcome this, decentralized controllers have been used earlier with conventional PI controller. It has gained focus in last few years, with major advantage, that for each area, local controller can be designed utilizing the locally available information [19][20]][21]. Cyber-attack and other uncertainties are considered as unknown inputs in [21] during designing of decentralized frequency controller.

With this background, a novel MOQDFO controller is designed in this study for frequency regulation in a multi area power system with many coupled links, and its comparative analysis vis-à-vis earlier developed observer controllers and optimal controller is presented.

On the basis of literature review, observers can broadly be classified as given in Table I, including the one proposed in this paper, on the basis of the order of observer mentioning the features and limitations thereof. Fig. 1 shows the classification of observer based load frequency controller in multi area power system.

TABLE I. CLASSIFICATION OF OBSERVERS

| Sl. No. | Type of observer | Features | Limitations |
|---|---|---|---|
| 1 | Full Order Observer | Easy to design | Very high order |
| 2 | Reduced Order Observer | Complicated design | The order of the system is (n-p), which is not a significant reduction in order in case of very large system |
| 3 | Centralized Functional Observer | Lower order and easy to implement | Minimum order is limited to k(ν-1) where, k is the number of functions defined and ν is the observability index. Further, it is a Centralized Controller |

| | | | |
|---|---|---|---|
| 4 | Quasi-Decentralized Functional Observer | Each area has its own controller, it's easy to implement and robust in nature | Minimum order for each observer is (ν-1), just one less than the observability index |
| 5 | Proposed MOQDFO Controller | Easy to design, Decentralized, Single order for each area observer | Nothing specific |

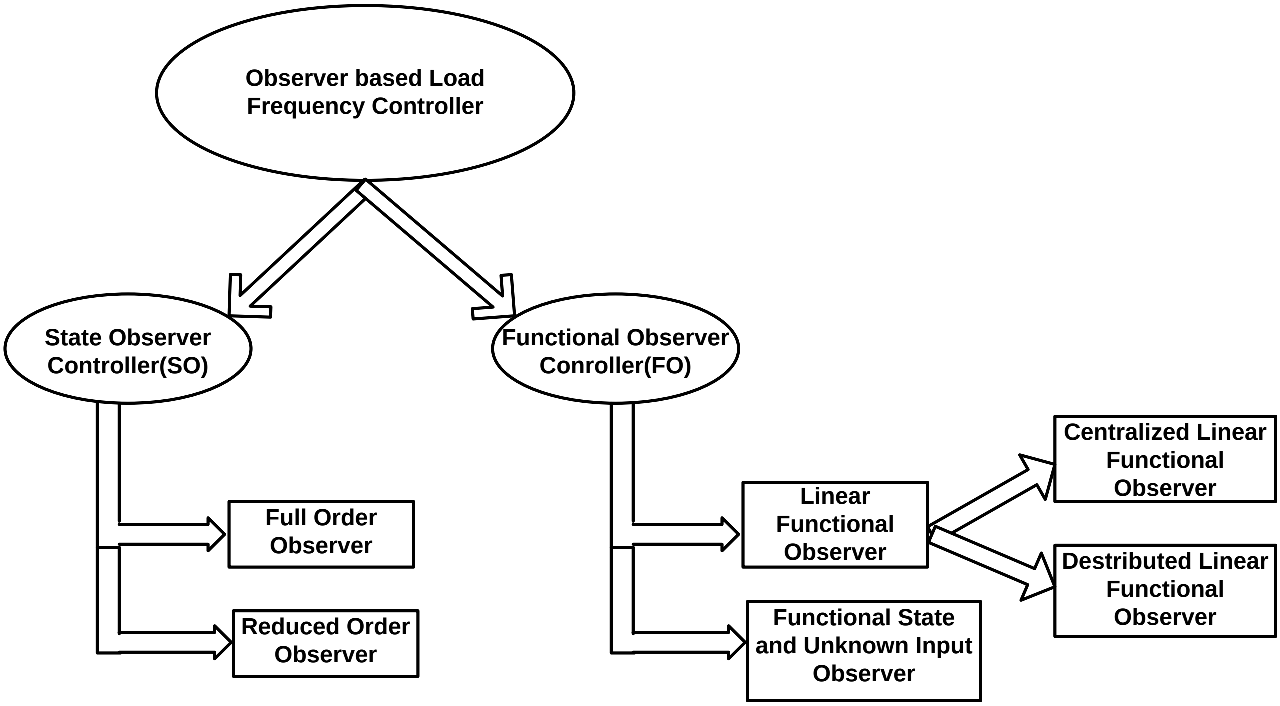

Figure 1. Broad classification of Observer based load frequency controllers for multi area power system

### A. *Linear Functional Observer*

Linear functional observer instead of observing all states of the system observes only a set of linear equations. All state feedback controlled inputs in feedback control system have the feature of independent linear equation which can be observed with LFO and this feature finds merit in designing a LFC for a large multi-area power system with the observer being of sufficiently reduced order. Minimum order of functional observer introduced was min $\{k(\nu - 1), (n - p)\}$ with symbols having their usual meanings as defined earlier and for many decades it was considered to be the minimum order of functional observer.

In LFO, it is possible estimating k independent linear functions of state vector with an order of k(ν-1) [15] [23]. State model of an n-area power system may be expressed as under:

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

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

Where, $A \in R^{nXn}$, $B \in R^{nXk}$ and $C \in R^{pXn}$

$u(t) = -Kx(t)$, the input control vector as per optimal control

Where, K matrix is evaluated by Ricatti equation.
Let the observer be designed with the following dynamics to observe input vector

$$\hat{z}(t) = w(t) + Ey(t) \tag{3}$$

$$\dot{w}(t) = \alpha w(t) + Jy(t) + Hu(t) \tag{4}$$

Where, $\hat{z}(t)$ estimates the control vector Kx(t) which is linear in nature and the error vectors defined as $e(t)$

$$\begin{aligned} e(t) &\triangleq \hat{z}(t) - Kx(t) \\ e(t) &\triangleq w(t) + Ey(t) - Kx(t) \\ &\triangleq w(t) + ECx(t) - Kx(t) \\ &\triangleq w(t) - (K - EC)x(t) \end{aligned}$$

Let $(K - EC) = M$

$\hat{z}(t)$ asymptotically estimates Kx(t) if and only if error vector $e(t) \to 0$ as $t \to \infty$ which leads to

$$(K - EC) - M = 0 \tag{5}$$

Differentiation of error can be written as
$\dot{e}(t) \triangleq \dot{w}(t) - M\dot{x}(t)$

To find conditions to match the above
$\triangleq (\alpha w(t) + Jy(t) + Hu(t)) - M\{Ax(t) + Bu(t)\}$
$\triangleq \alpha\big(w(t) - Mx(t)\big) + (\alpha M + JC - MA)x(t) + (H - MB)u(t)$
$\triangleq \alpha e(t) + (\alpha L + JC - MA)x(t) + (H - MB)u(t)$
In order to make $\dot{e}(t) \rightarrow 0$ as $t \rightarrow \infty$ , $\alpha$ must be Hurwitz,
$\alpha M + JC - MA = 0$
$H - MB = 0$
To design LFO, we need to solve following equations

$$\alpha M + JC - MA = 0 \quad (6)$$
$$K - EC - M = 0 \quad (7)$$
$$H - MB = 0 \quad (8)$$

These are the three decoupled equations and $\alpha$, J, L, and H are the unknown matrices which need to be solved for which the technique is given in [24].
To design minimum order LFO, the following conditions must be satisfied

1. $\text{rank}\begin{bmatrix} KA \\ CA \\ C \\ K \end{bmatrix} = \text{rank}\begin{bmatrix} CA \\ C \\ K \end{bmatrix}$
2. $\text{rank}\begin{bmatrix} sK - KA \\ CA \\ C \\ K \end{bmatrix} = \text{rank}\begin{bmatrix} CA \\ C \\ K \end{bmatrix}$

With these conditions having been met only the observer of order k could be designed with given methods. Otherwise, the minimum possible order is more than k and less than $\min\{r(v-1), (n-p)\}$[18].
For solving the above equation, partition the two area equations such that

$\widetilde{K} = KP = [K_1 \; K_2]$
$\widetilde{A} = P^{-1}AP = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$
$\widetilde{M} = MP = [M_1 \; M_2]$

By substituting all these values in above equations
$J = M_1A_{11} + M_2A_{21} - M_1;$ (9)
$K_2 = M_2;$
$\alpha M_2 - M_1A_{12} - M_2A_{22} = 0$ (10)
H=MB; and α must be Hurwitz.
Functional observability conditions from [15] tend to

$$\text{rank}\begin{bmatrix} K_2A_{12} \\ A_{12} \\ K_2 \end{bmatrix} = \text{rank}\begin{bmatrix} A_{12} \\ K_2 \end{bmatrix}$$

$$\text{rank}\begin{bmatrix} s - K_2A_{12} \\ A_{12} \\ K_2 \end{bmatrix} = \text{rank}\begin{bmatrix} A_{12} \\ K_2 \end{bmatrix}$$

For solving, post multiply (10) by full rank matrix $[{K_2}^{+} \; K_2^{\perp}]$ where, ${K_2}^{+}$ is Moore-Penrose inverse of $K_2$ and $K_2^{\perp}$ is orthogonal basis for the null space of $K_2$.

$M_1A_{12}{K_2}^{+} = -K_2A_{22}{K_2}^{+}$
$\propto = M_1A_{12}K_2^{\perp} = -K_2A_{22}K_2^{\perp}$
it gives solution of
$$M_1 = \Omega\psi^{+} + L(I_p - \psi\psi^{+}) \quad (11)$$
where, $\psi = A_{12}K_2^{\perp}$ and $\Omega = -K_2A_{22}K_2^{\perp}$
where, L is an arbitrary equation in order to place α at some location in s-plane.
These equations conclude as

$\propto = \propto_1 - L \propto_2$
$\propto_1 = (\Omega\psi^{+}A_{12} + K_2A_{22})\,{K_2}^{+}$
and $\propto_{2=} (\psi\psi^{+} - I_p)A_{12}K_2^{+\,+}$

Functional observability implies that $\alpha_2$ and $\alpha_1$ are detectable and L can be found with any pole placement method. Once L is found, α and $M_1$ can be calculated and all other unknown matrices can be determined. Now M is of minimum order, same as the no. of areas connected, and can be computed or taken the same as the number of controlled inputs/no. of functions defined for observer. The system block diagram is depicted in Fig. 2 with LFO controller.

### B. *Minimum Order Quasi-Decentralized Linear Functional Observer*

Centralized LFO has the limitation of transportation of state vectors and controller data over long distance. For many decades, decentralized controllers have been actively pursued in research with PI controllers. Quasi-Decentralized Functional Observer has been defined in [11] where each area has its own observer controller that is dependent on other area's output as well. The proposed controller schematic is depicted in Fig. 3.

For the system defined in (1) & (2) for n area, j=1.......n
Each input for individual j<sup>th</sup> area is defined as $u_j(t) = F_jx(t)$, LFO equations for j<sup>th</sup> interconnected area in system is given as

$$\hat{z}_j(t) = w_j(t) + E_jY(t) \quad (12)$$

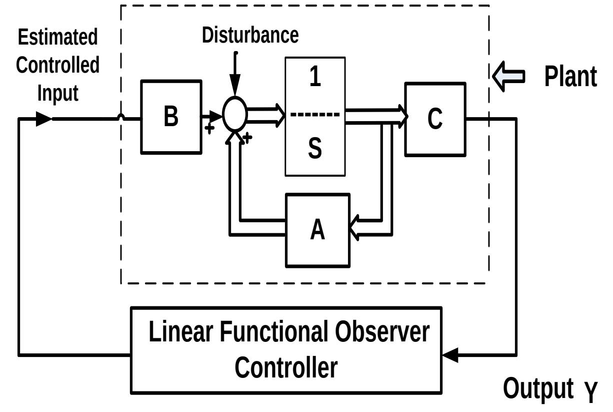

Figure 2. Block diagram of system with LFO controller

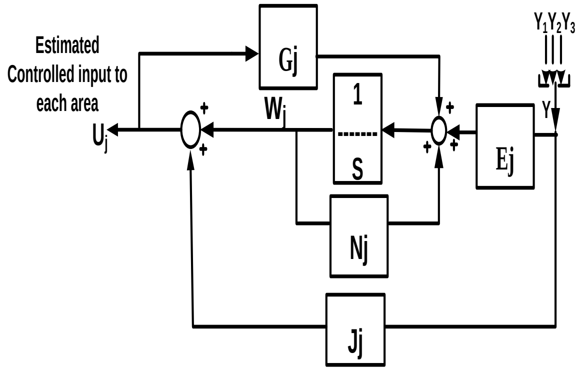

Figure 3. Block diagram of proposed observer controller

$$\dot{w}_j(t) = N_j w_j(t) + G_j u_j(t) + J_j Y(t) \quad (13)$$

$w_j(t)\,, K_j, E_j, N_j, and\ G_j$ are matrices of appropriate dimension.

State model equation for decentralized system can be re-written as

$\dot{x} = Ax(t) + \hat{B}_j(t)U_j(t) + \hat{B}_r U_r(t)$

$Y(t) = Cx(t)$

Where, $u_r(t) = [u_i\ u_{i+1}\ \ldots..u_r]$ $i \neq j$;

and $\hat{B}_r = [B_i\ B_{i+1} \ldots\ldots B_r]$ $i \neq j$;

$\hat{z}_j(t)$ estimates the control vector $F_j x(t)$ which is linear in nature and if there exists $M_j$ matrix such that

$\hat{z}_j(t) = M_j x(t)$

let error vectors for jth area are defined as $e_j(t)$ & $\Delta_j(t) = \dot{e}_j(t)$ be defined as

$e_j(t) \triangleq \hat{z}_j(t) - F_j x(t)$

$\Delta j(t) \triangleq K_j w_j(t) + E_j Y(t) - F_j x(t)$

In order for the errors to tend to zero as time t→ ∞, equations are given as

$$N_j M_j + J_j C - M_j A = 0 \quad (14)$$
$$M_j + E_j C - F_j = 0 \quad (15)$$
$$G_j - M_j \hat{B}_j = 0 \quad (16)$$
$$M_j \hat{B}_r = 0 \quad (17)$$

For solving these equations, $M_j$ will be solved from equation (17), as $\hat{B}_r$ is a known matrix [25].

Where, $N_j$ is Hurwitz and can be assigned arbitrary location if all the conditions are satisfied as in previous section.

To design the observer of minimum order, the observer parameters to be solved are as given below

$$\widetilde{\hat{B}_r} \triangleq P^{-1}\hat{B}_r = \begin{bmatrix} \hat{B}_{r_1} \\ \hat{B}_{r_2} \end{bmatrix}$$
$$\widetilde{M_j} \triangleq M_j P = [M_{j1}\ M_{j2}]$$
$$\widetilde{F_j} \triangleq F_j P = [F_{j1}\ F_{j2}]$$

Equation (15) can be rewritten as

$$M_{j1}B_{r1} + M_{j2}B_{r2} = 0 \quad (18)$$
$$J_j = -N_j M_{j1} + M_{j1}A_{11} + M_{j2}A_{21} \quad (19)$$
$$M_{j2} = F_{j2} \quad (20)$$
$$N_j M_{j2} - M_{j1}A_{12} - M_{j2}A_{22} = 0 \quad (21)$$

$M_{j1}$ can be computed from (18) & (20), $N_j$ from (21), $J_j$ from (19), and $G_j$ from (16). Now all observer parameters are available and therefore, the observer can be designed as per the dynamic equation.

## 3. CASE STUDY SYSTEM

Here, three area power system is considered which is interconnected with transmission links (high voltage DC (HVDC) and TCPS) to add more practicality, as shown in Fig. 4, and each area has multi-source structure as combination of reheated thermal turbine and BESS in order to support frequency in case of sudden load change. Area parameters are adapted from [12] where the detailed description of system could also be referred from. However, for completeness, brief description of the system is in order and given hereunder.

To realize the real power system world, power areas are considered to be connected through HVDC Link and AC link in parallel. Motivation to use both HVDC and AC Links in parallel is drawn from its feasibility for technical and economic reasons. These transverse links are utilized for exchanging power among control areas and also for providing frequency support in the event of sudden load. Power transmission over long distances with

AC links causes large oscillations, high transmission losses, and deteriorated overall system performance. HVDC transmission is connected with electronic devices, improves controllability and reduces problems associated with Links and increases economic feasibility. It has been studied for many long years that it is advantageous to use HVDC with AC links in multi area power systems integrated with multiple sources. Many recent studies have shown advantages, improved dynamic performance and impact of HVDC link in power system [26][27].

### A. HVDC Link

Power flow of DC Link between two area 1 & 2 in terms frequency is given as below [12].

$$\Delta P_{DC12} = \frac{K_{DC12}}{sT_{DC12}+1}(\Delta f_1(s) - \Delta f_2(s))$$

Where, $\Delta P_{DC12}$ is the DC power transfer between area 1 and 2, $K_{DC12}$ is the DC gain constant, $T_{DC12}$ is the DC time constant, and $\Delta f_1(s)$, $\Delta f_2(s)$ are the frequency deviations in respective areas. The interconnection of HVDC links for multi area power system is shown in Fig. 5 with $K_{ij}$=1 if area i and j are connected with HVDC link and Kij=0 if areas i and j are not connected with HVDC link.

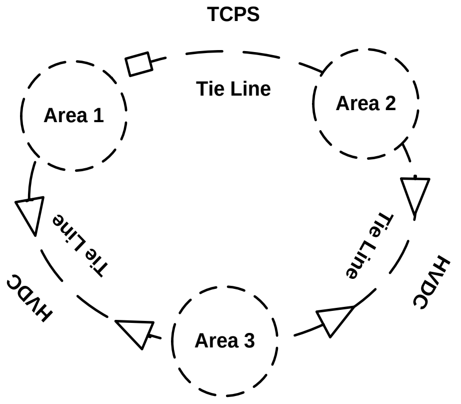

Figure 4. Three area power system interconnected with TCPS, HVDC, and AC links

### B. Battery Energy Storage System

It involves a battery bank coupled to the AC power network via a power converter. Many researchers have developed various configurations of BESS. With rapidly evolving technology of power electronic devices, it is now possible to exercise quick control over active and reactive power outputs of the BESS. The conversion of power from DC to AC and vice versa can be attained through these fast acting power switching devices [28][29]. Most common applications of BESS include load leveling, mitigation of harmonics, voltage control, and in damping out power swings with an overall aim of improving the transient and dynamic stability [28][29].

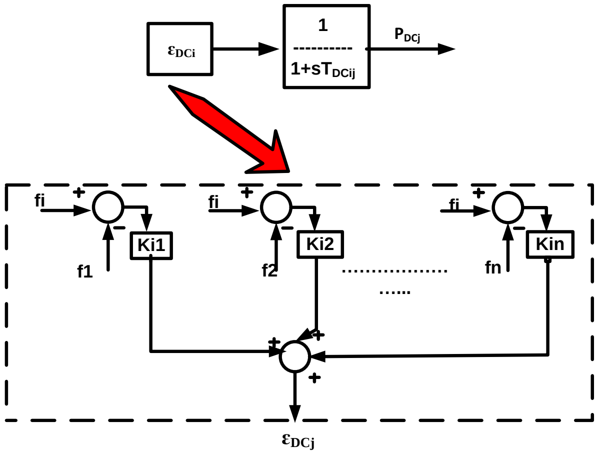

Figure 5. Dynamic model of HVDC link between area i and j

The BESS can quickly change its mode of operation between charging and discharging and thereby can take care of any transient conditions in the power system arising out of some disturbance. The BESS can be described as the first order transfer function [30]. Here, we have considered the bank of enough no. of batteries to provide power backup support in case of sudden change of load.

The transfer function of BESS is given as

$$\Delta P_{BESS} = \frac{K_{BESS}}{sT_{BESS}+1}\Delta f$$

Where, $\Delta P_{BESS}$ signifies the variation in BESS output power, $K_{BESS}$ represents the BESS gain constant, $T_{BESS}$ is time constant of BESS, and $\Delta f$ is change in frequency.

### C. Thyristor Controlled Phase Shifter

Due to numerous advantages and flexibility of FACTS devices, now-a-days transmission lines are extended with FACTS devices connected in series or shunt as per requirement. Here TCPS is considered to be connected in series of transmission lines with the linearized dynamic model of TCPS described below. Effect of TCPS on power transfer, if it is connected on area one, can be expressed in Tie Line power flow perturbation as under [31]. Fig. 6 depicts the block diagram showing the effect of TCPS and HVDC link.

$$\Delta P_{tie12} = \frac{T_{12}(\Delta w_1(s) - \Delta w_2(s))}{s} + \frac{T_{12}K_{TCPS}}{sT_{TCPS}+1}\Delta w_1(s)$$
$$= \Delta P_{AC12} + \Delta P_{TCPS}$$

Where, $K_{TCPS}$, and $T_{TCPS}$ are the gain and time constants, respectively, of TCPS, $T_{12}$ is tie line time constant,

$\Delta P_{AC12}$ and $\Delta P_{TCPS}$ are, respectively, the power variations of the AC link and the TCPS. Further, $\Delta w_1$=2π$\Delta f_1$ and $\Delta w_2$=2π$\Delta f_2$.

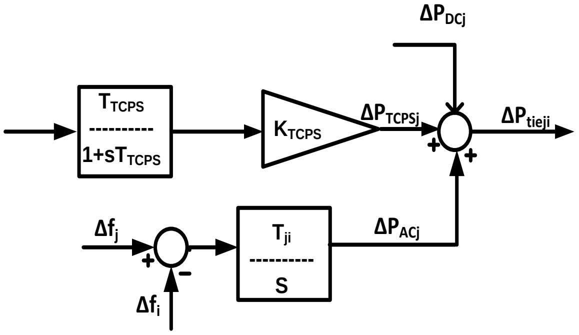

Figure 6. Block diagram depicting change in tie line power with effects of TCPS and HVDC links

### D. *State Space Model of Test System*

A typical block diagram of 3 areas, interconnected with TCPS, HVDC, AC Links, and a non-reheated power system with BESS as additional energy source in LFC model, is depicted in Fig. 7. Each area dynamics of multi-area power system can be represented in terms of state model as

$$\dot{x}(t) = Ax(t) + Bu(t) + Wd(t)$$
$$y(t) = Cx(t)$$

Where, x, u, d, and y are the state, input, disturbance, and the output vectors, respectively and where, A∈$R^{23X23}$, B ∈$R^{23X3}$, W ∈$R^{23X3}$ , and C ∈$R^{14X23}$

Input vector control as per optimal control law can be described as

$$u = -Kx(t)$$

State vector for j$^{th}$ area with j=1, 2, and 3 is given as

$$x_j = (\Delta f_j, \Delta X_{gj,} \Delta P_{rj}, \Delta P_{gj}, \Delta P_{BESSj}, \int ACEj, \Delta P_{tiej}, \Delta P_{dcj,} \Delta P_{TCPSj})$$

$$\Delta \dot{f}_j \triangleq -\frac{D_j}{M_j}\Delta f_j + \frac{1}{M_j}\Delta P_{gj} + \frac{1}{M_j}\Delta P_{ej} - \frac{1}{M_j}\Delta P_{tiej} - \frac{1}{M_j}\Delta W_j$$

$$\Delta \dot{X}_{gj} \triangleq -\frac{K_{gj}}{R_j T_{gj}}\Delta f_j - \frac{1}{T_{gj}}\Delta X_{gj} + \frac{\alpha_{gj}K_{gj}}{T_{gj}}\int \Delta P_{tiej}$$

$$\Delta \dot{P}_{gj} \triangleq -\frac{1}{T_{rj}}\Delta P_{gj} + \frac{K_{Tj}K_{rj}}{T_{Tj}T_{rj}}\Delta X_{gj} + \frac{1}{T_{rj}}\left(1 - \frac{K_{rj}}{T_{Tj}}\right)\Delta P_{rj}$$

$$\Delta \dot{P}_{rj} \triangleq -\frac{1}{T_{rj}}\Delta P_{rj} + \frac{K_{Tj}}{T_{Tj}}\Delta X_{gj}$$

$$\Delta \dot{P}_{BESSj} = -\frac{1}{T_{BESSj}}\Delta P_{BESSj} + \frac{\alpha_{BESSj}K_{BESSj}}{T_{BESSj}}\int \Delta P_{tiej}$$

$$ACE = B_j \Delta f_j + \Delta P_{tiej}$$

$$\Delta \dot{P}_{DCj} = -\sum_{j=1 j\neq i}^{n} \frac{K_{ji}}{T_{dcj}}(\Delta f_j - \Delta fi) - \frac{1}{T_{dcj}}\Delta P_{dcj}$$

$$\Delta \dot{P}_{ACji} = 2\pi T_{ji}(\Delta f_j - \Delta fi)$$

$$\Delta \dot{P}_{TCPSj} = -\frac{1}{T_{TCPS}}\Delta P_{TCPS} + \frac{\Delta f_j}{T_{TCPS}}$$

### E. *Optimal State Feedback Control for LFC*

Observer based controllers are employed for the interconnected power network. For computing state feedback gain matrix with specific weighting matrices, linear quadratic regulator (LQR) methodology derived on algebraic Riccati equation is made use of. Penalties are enforced, via the weighting matrices, proportionate to the variation of trajectories vis-à-vis the estimated state variables and control signal (u) with the performance index being expressed as

$$J = \int (x'(t)\, Qx(t) + u'(t)Ru(t))dt$$

Where, Q (nxn) and R (mxm) are, respectively, the state cost and control cost weighting matrices which are both positive semi definite and symmetric in nature and are suitably selected. The control law for minimizing the system cost can be expressed, being dependent on current values of the system state variables weighted by the elements of a constant gain matrix K (mxn), as $u = -K$x(t), with K being computed via reduced matrix Riccati equation as under

$$A'P + PA - PBR^{-1}B'P + Q = 0$$

Where, K=$R^{-1}B'P$ is optimal state feedback constant and can be represented as $K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix}$

### F. *System Parameters*

Parameters for all the three areas are considered as same and provided hereunder in Table II.

TABLE II. SYSTEM PARAMETERS

| **SI. No.** | **Parameters** | **Value** |
|---|---|---|
| 1 | $T_{t1}$=$T_{t2}$=$T_{t3}$ | 0.3 |
| 2 | $K_{t1}$= $K_{t2}$= $K_{t3}$ | 1 |
| 3 | $T_{r1}$= $T_{r2}$= $T_{r3}$ | 10 |
| 4 | $K_{r1}$= $K_{r2}$= $K_{r3}$ | 0.5 |
| 5 | $T_{g1}$= $T_{g2}$= $T_{g3}$ | 0.08 |

| | | |
|---|---|---|
| 6 | $K_{g1}= K_{g2}= K_{g3}$ | 1 |
| 7 | $M_1=M_2= M_3$ | 1/6 |
| 8 | $D_1= D_2= D_3$ | 0.0083 |
| 9 | $K_{BESS}= K_{BESS}= K_{BESS}$ | 1 |
| 10 | $T_{BESS}= T_{BESS}= T_{BESS}$ | 1 |
| 11 | $R_1 =R_2= R_3$ | 2.4 |
| 12 | $B_1=B_2=B_3$ | 0.425 |
| 13 | $T_{12} =T_{23}= T_{31}$ | 0.0260 |
| 14 | $T_{DC1}= T_{DC3}$ | 0.2 |
| 15 | $K_{TCPS}$ | 1 |
| 16 | $T_{TCPS}$ | 0.1 |

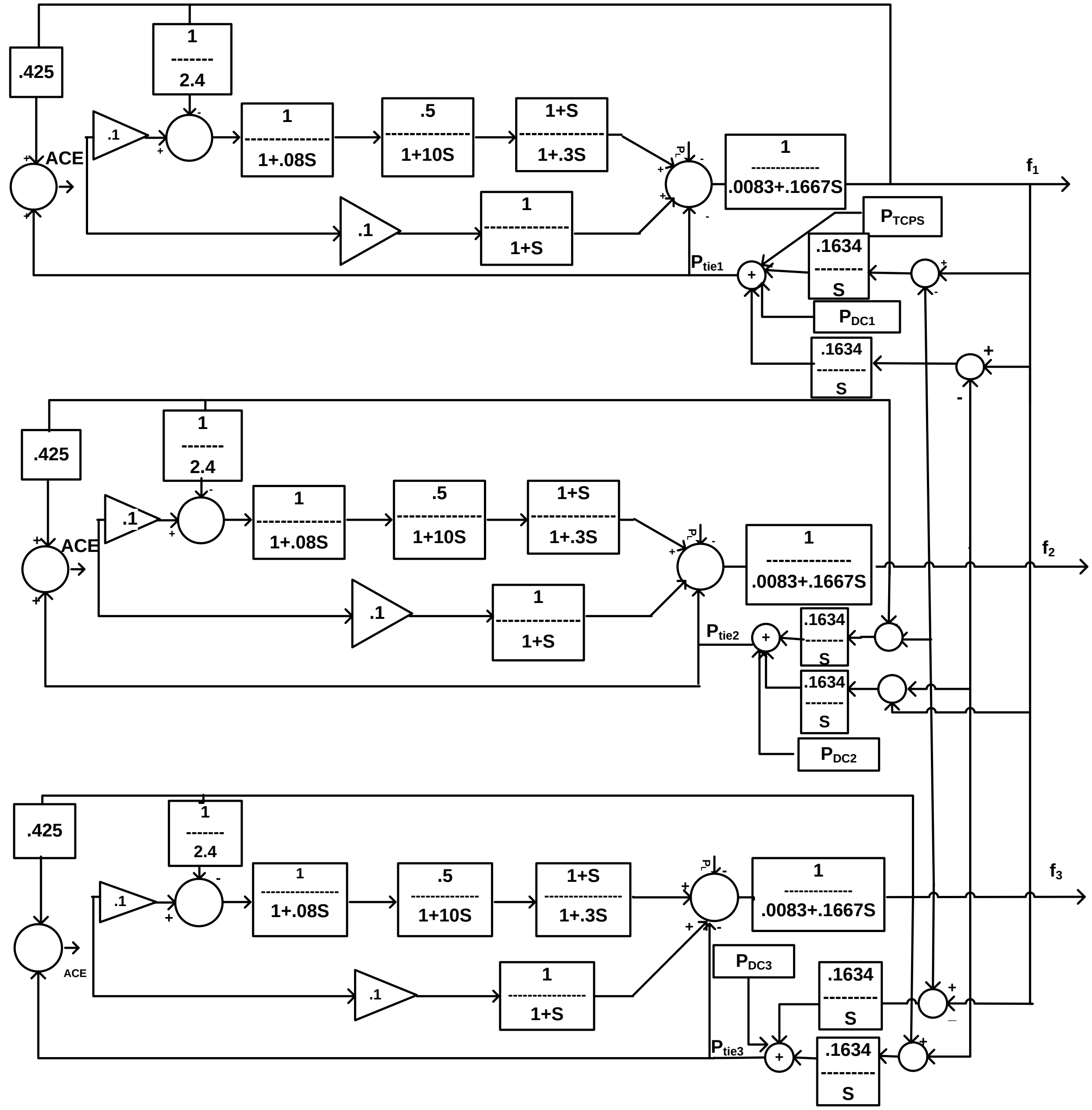

Figure 7. Transfer function model of three area power system with TCPS, HVDC, and BESS

## 4. RESULTS AND DISCUSSION

All matrix equations are formulated and executed in MATLAB as .m files and the power system design, as in Fig. 7 and Fig. 8, is simulated in MATLAB Simulink. First, open loop three area system is studied, with and without HVDC and TCPS links, to evaluate the frequency regulation performance against 1% step load disturbance applied in area-1, which is shown in Fig. 9 with Fig. 10 showing the Tie line power response. From these figures, it can be observed that with the HVDC and TCPS links connected in the system, the oscillations get damped faster and the peak overshoot also reduces, meaning thereby that the integration of TCPS and HVDC Links in parallel helps improve the LFC performance.

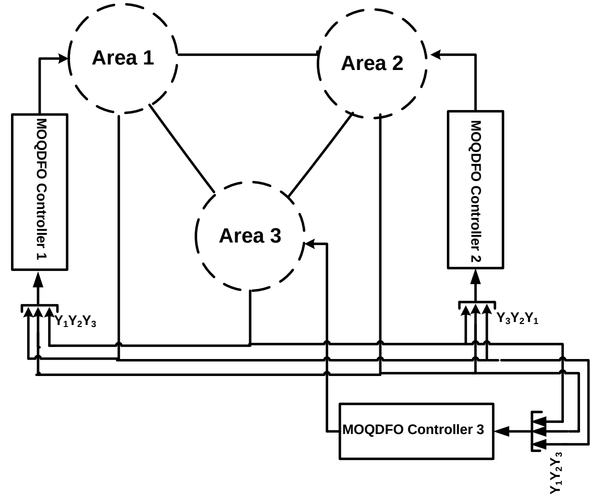

Figure 8. Minimum order quasi decentralized functional observer controller connections in three area system

Further, the optimal controllers, estimated conventional observer controllers, and the proposed controllers are designed as per the methodologies explained in the previous sections and the system is investigated with these controllers in place. The system frequency regulation performance and also the performance with regards tie line power, with these controllers in place, are investigated under the same 1% step load disturbance and the relative comparison of performances is given in Figs. 11 and 12, respectively. As is evident seeing these figures, the proposed MOQDFO controller gives improved result and almost mimics the optimal controller. Figs. 13, 14, and 15 are the estimated inputs as compared to optimal controller inputs for different areas and the proposed controller is very fast in reaching to zero error between the optimal and estimated values.

With a view to assess the proposed controller for robustness, investigations are carried out against random load disturbance, as per the pattern shown in Fig. 16, as well with frequency and tie-line power response obtained over a time span of 100 s which is shown in Figs. 17 and 18, respectively. It can be brought out from Figs. 17 and 18 that the controller follows the random variations very closely and is able to effectively arrest the deviations in frequency and tie-line power thus proving that the proposed control scheme is robust.

The quantitative assessment of the performance of the proposed controller and also that of other controllers, for comparison purpose, can be seen through Table III in respect of peak overshoot and the order of the controllers. The analysis of Table III data makes it amply clear that the proposed MOQDFO controller gives the best performance with the values of peak overshoot of frequency and tie line power deviations, respectively, being 2.577% and 24.375%, which are the least among all controllers. Further, the order of the proposed controller is 1 which is the lowest.

TABLE III. QUANTITATIVE PERFORMANCE PARAMETERS

| **SI. No.** | **Type of Controller** | **% Peak Overshoot** | | **Order of Controller** |
|---|---|---|---|---|
| 1 | Optimal Controller | f | 11.798 | 23 |
| 2 | | $P_{tie}$ | 46.078 | |
| 3 | Full Order Observer Controller | f | 40.141 | 23 |
| 4 | | $P_{tie}$ | 50.758 | |
| 5 | Reduced Order Observer Controller | f | 71.592 | 9 |
| 6 | | $P_{tie}$ | 47.581 | |
| 7 | Proposed Controller(MOQDFO) | f | 2.577 | 1 |
| 8 | | $P_{tie}$ | 24.375 | |

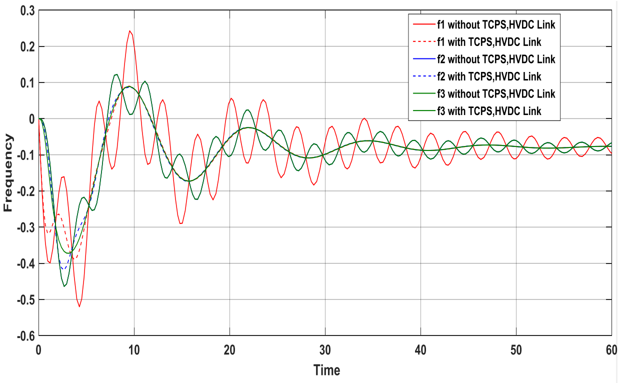

Figure 9. Open loop frequency response of all areas for .01 p.u. step load disturbance at area 1

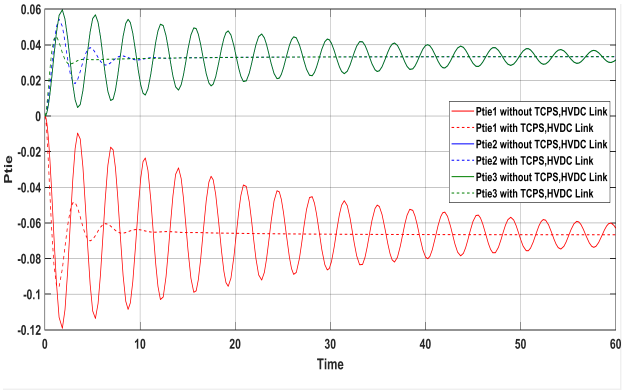

Figure 10. Open loop tie line power response of all areas for .01 p.u. step load disturbance at area 1

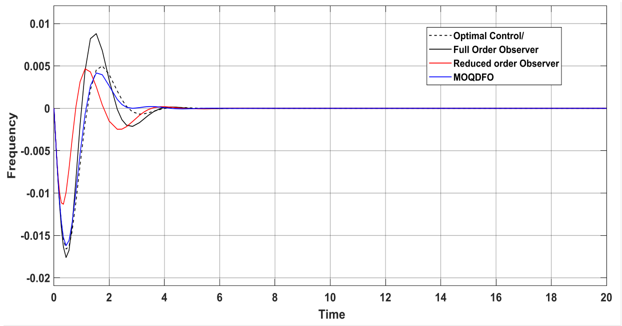

Figure 11. Frequency response of area 1 for .01 p.u. step load disturbance at area 1 with observer controllers

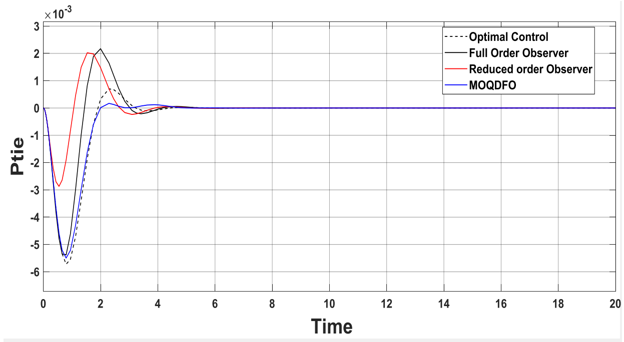

Figure 12. Tie line power response of area 1 for .01 p.u. step load disturbance at area 1 with observer controllers

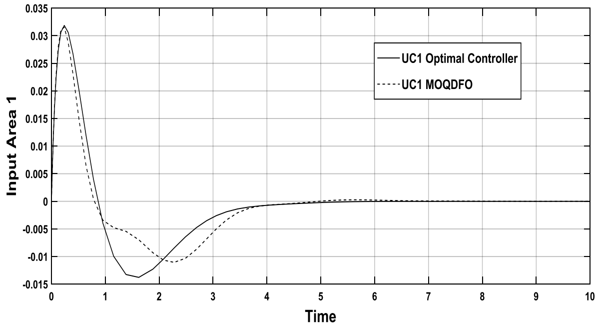

Figure 13. Estimated controller input $U_1(t)$ for area 1

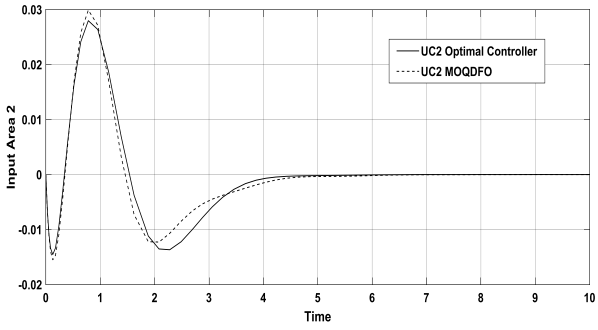

Figure 14. Estimated controller input $U_2(t)$ for area 2

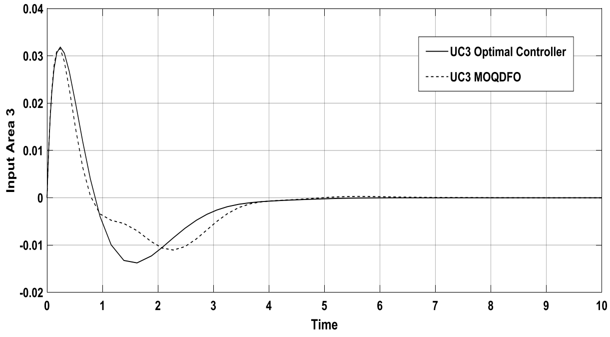

Figure 15. Estimated controller input $U_3(t)$ for area 3

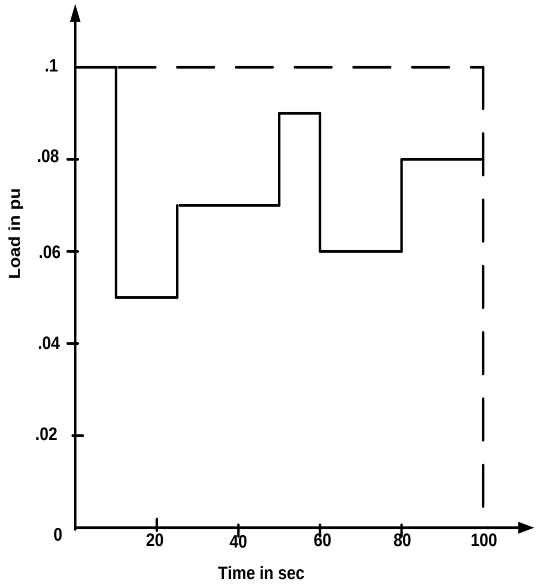

Figure 16. Random load pattern

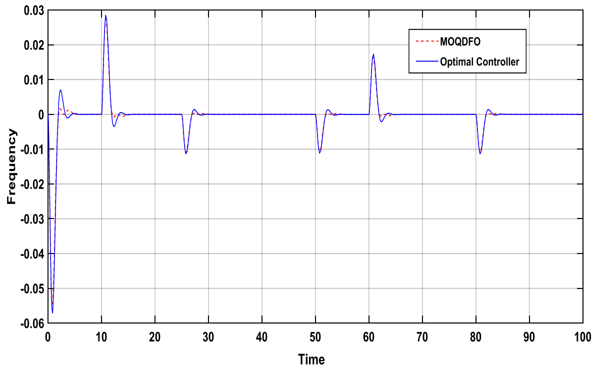

Figure 17. Frequency response for area 1 with random load pattern at area 1

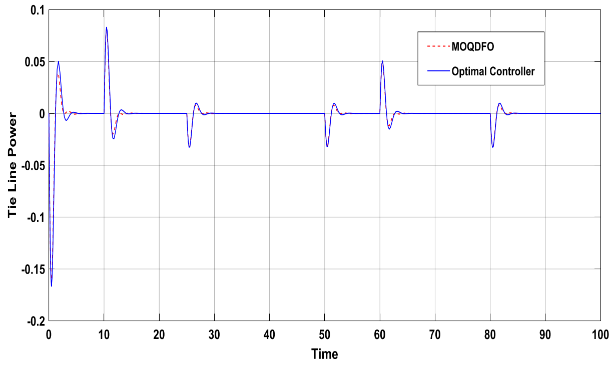

Figure 18. Tie line power response for area 1 with random load pattern at area 1

## 5. CONCLUSION

The paper has designed and implemented a novel distributed controller of minimum (single) order for frequency regulation in three-area interconnected power network under different load patterns. The proposed controller turns out to be giving very effective and improved results compared to the other controllers implemented here for comparison purpose. Besides, the impact of TCPS and HVDC links is also studied and it is established that these links show positive impact on both frequency as well as tie line power response. This novel proposition reduces the system complexity of 23rd order to a single order functional observer controller. The comprehensive simulation results for different scenarios prove the efficacy and robustness of the proposition and of course its usefulness for a practical system.

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