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Decentralized Disturbance Rejection Control of Multi-Area Power Systems Using Generalized Extended State Observer

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Abstract: *In this paper, generalized extended state observer is implemented to the load-frequency control of a multi-area power system. By using this observer, there is no need to have an accurate dynamic model of the system and thus, leads to a more robust performance against the uncertainties of the system parameters and disturbances in comparison with conventional load-frequency control methods. Moreover, the higher order disturbances rather than just step disturbances can be rejected by the proposed method, because of estimating the both disturbance and its derivative. A generalized disturbance signal is defined for each area. It consists of unmodeled dynamics of the system, external disturbances, and the interactions of the other areas. In the proposed control strategy, the generalized disturbance is estimated using local input and output data by a local state observer. Then, the estimation of generalized disturbance is used in a local state feedback controller to reject it and track the related references. The simulation results show the effectiveness of the proposed method.*

Keywords: decentralized control, disturbance rejection, generalized extended state observer, large-scale systems, multi-area power systems.

1. Introduction

The both active power balance and reactive power balance are very important in a transmission network. The active power is related to frequency control and the reactive power is related to voltage control, hence, they can be separately controlled. The control of active power and frequency is referred to as load-frequency control (LFC) [1].

The large-scale power systems are usually composed of several units of generation. Hence, they are also called multi-area power systems. The units of a multi-area power system are interconnected via tie-lines to improve the fault tolerance of the entire system. The flows of power on the tie-lines, cause the so-called tie-line power exchange error to the control system. Hence, in a multi-area power system, in addition to the frequency, the power interchange on the tie-lines has to be controlled and maintained at scheduled value [1].

The main objectives of a load-frequency control system are:

(1) to hold the system frequency at the nominal value,

(2) to maintain the power flows on the tie-lines at preset value, and (3) to share the amount of required generation among generating units as scheduled [2].

Conventional controllers such as PI and PID controllers are extensively used in the industry for load-frequency control. In fact, most of these controllers are designed based on nominal values of system parameters. But, LFC design based on the nominal system parameters does not guarantee the stability and the desired performance of the power system under parametric uncertainties. This problem leads to using of adaptive and robust methods in load-frequency control.

The adaptive control of multi-area power systems has been investigated by many researchers to make the controller insensitive to the variation of the plant parameters [2-5]. A decentralized adaptive control scheme is proposed in [2] for load-frequency control of multi-area power systems using the concept of overlapping decomposition. It was considered each local area network to be overlapped with states representing the interconnections with the other local area. Then, the decentralized control scheme was developed as a function of the local area state variables and those resulting from the overlapped states which represent an approximation of the interconnection variables.

An adaptive decentralized load-frequency control of multi-area power systems has been presented by Zribi et. al. in [3]. They proposed a decentralized adaptive load-frequency control scheme based on the Lyapunov theory to cope with changes in the parameters of power systems.

However, these methods require either information on the system states or an efficient on-line identifier. Model reference adaptive techniques are required for satisfying the perfect model following conditions and the complete system state information. Since the order of the multi-area power system is large, these approaches may be difficult to apply [4,5].

In the most control strategies, the interactions are considered as external disturbances [6,7]. It yields the controller to be more conservative. But M.H. Kazemi et. al. in [8] proposed a method for reconstruction of the interactions which were used in control design strategies to achieve better results and less conservative performance. For each local area, a local estimator was designed to estimate the interactions of this area using only the local output measurements and then it was exploited by the local controllers to compensate the effect of interactions.

Many researchers tried to obtain a systematic PID controller tuning method for load-frequency control of large-scale power systems. In this area of research, [9-11] proposed to tune PID load-frequency controller via two-degree-of-freedom internal model control (IMC) technique to remove the oscillation of disturbance response of one-degree-of-freedom internal model control. It was shown that with two tuning parameters the method can achieve good performance for load-frequency control of power systems and it have been extended to the decentralized case for multi-area power systems.

Disturbance rejection control methods [12-17] are also studied in the literature for the LFC problem of interconnected power systems. L. Dong and Y. Zhang in [16] used the active disturbance rejection control based on extended state observer discussed in [14,15] for load-frequency control of multi-area power systems. The designed controller seems good but the observer can only estimate the step load disturbances. R. Miklosovic et al. in [17] generalized the extended state observer to estimate the higher order disturbances.

Thus, in this paper, the active disturbance rejection control proposed in [16] and the generalized extended state observer designed in [17] are used for load-frequency control of a three-area power system.

The paper is organized as follows: The dynamic of the system under study and the problem statement are presented in section 2. The formulation of Active Disturbance Rejection Control(ADRC) based on Extended state observer (ESO) and generalized extended state observer(GESO) are given in Section 3. In section 4, a load-frequency controller is designed for the system under study to demonstrate the feasibility of the proposed approach. The simulation results are presented in section 5. The effects of model parameter variations is also considered in this section. Finally, some conclusions are given in section 6.

2. System Description and Problem Formulation

A typical multi-area power system is composed of several areas or subsystems of generating units those are connected via tie-lines.

For the objective of load-frequency control, each area of the system can be represented by the linear model obtained by linearizing the plant around the operating point [1].

The system under study is a three-area power system. The block diagram of area 1 is shown in Fig. 1. The other areas are the same as area 1.

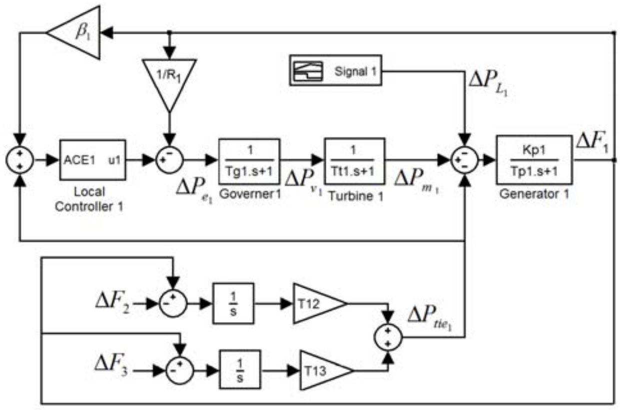

Fig. 1: block diagram for area 1 of a three-area power system

As you can see in this figure, the frequency deviations of area 2 and 3 enter to area 1 and form the so-called interaction term of area 1.

According to Fig. 1, the following equations stand for each area.

$$
\begin{aligned}
&U_i(s) - \frac{1}{R_i}\Delta F_i(s) = \Delta P_{e_i}(s) \\
&G_{Gov_i}\Delta P_{e_i}(s) = \Delta P_{v_i}(s) \\
&G_{Tur_i}\Delta P_{v_i}(s) = \Delta P_{m_i}(s) \\
&\left(\Delta P_{m_i}(s) - \Delta P_{L_i}(s) - \Delta P_{tie_i}(s)\right) G_{Gen_i} = \Delta F_i(s)
\end{aligned} \tag{1}
$$

where, $G_{Gen}(s)$, $G_{Tur}(s)$ and $G_{Gov}(s)$ represent the transfer functions of the generator, turbine and governor respectively. These transfer functions are defined as

$$
\begin{aligned}
&G_{Gov_i}(s) = \frac{1}{T_{G_i}s+1} \\
&G_{Tur_i}(s) = \frac{1}{T_{T_i}s+1} \qquad i = 1,2,3 \\
&G_{Gen_i}(s) = \frac{K_{P_i}}{T_{P_i}s+1}
\end{aligned} \tag{2}
$$

And the parameters used in equations (1) and (2) are as follows:

R_i : droop characteristic for area #i (Hz/p.u. MW)

ΔF_i : incremental frequency deviation of area #i (Hz)

$\Delta P_{tie_{ij}}$: incremental change in tie-line power between area #i and other areas (p.u. MW)

T_{T_i} : turbine time constant in area #i (s)

ΔP_{L_i} : load disturbance in area #i (p.u. MW)

K_{P_i} : electric system gain in area #i

T_{P_i} : electric system time constant in area #i (s)

T_{ij} : synchronizing coefficients between area #i and #j (p.u. MW/Hz)

The load disturbances lead to frequency deviations and tie-line exchange error in system areas. The frequency deviation combined with the tie-line power exchange deviation, form the so-called area control error(ACE) that have to be removed (ACE=0) by the load-frequency control system to achieve the objectives discussed in section 1.

$$ACE_i = \beta_i \Delta F_i(s) + \Delta P_{tie_i}(s) \tag{3}$$

This signal is defined as the output of the load-frequency control system which has to be controlled.

$$Y_i(s) = \beta_i \Delta F_i(s) + \Delta P_{tie_i}(s) \tag{4}$$

As a result, for each area we can write:

$$Y_i(s) = G_{P_i}(s) U_i(s) + G_{tie_i} \Delta P_{tie_i} + G_{d_i} \Delta_{P_{L_i}} \tag{5}$$

And the input to output transfer function of each area is of the form

$$\begin{aligned} \frac{Y_i(s)}{U_i(s)} &= G_{P_i}(s) = \frac{\beta_i G_{Gen_i} G_{Tur_i} G_{Gov_i}}{1 + \frac{1}{R_i} G_{Gen_i} G_{Tur_i} G_{Gov_i}} \\ &= \frac{R_i \beta_i K_{P_i}}{R_i (T_{P_i} s + 1)(T_{T_i} s + 1)(T_{G_i} s + 1) + K_{P_i}} \end{aligned} \tag{6}$$

3. Disturbance Rejection Control

Estimating the disturbance and using this estimation in the control law to reject the disturbance is the main idea of disturbance rejection control.

Suppose that the system equation is given by:

$$y^{(n)} = bu + d \tag{7}$$

Then if we can estimate the disturbance d by an observer, we can reject it approximately by the control law given by:

$$u = \left(u_0 - \hat{d}\right)/b \tag{8}$$

where, $\hat{d}$ is the estimation of disturbance d.

With the control law (8) , the plant (7) will reduce to a pure integral plant given by:

$$y^{(n)} = b\left(u_0 - \hat{d}\right)/b + d \tag{9}$$

$$y^{(n)} \approx u_0 \tag{10}$$

Then a state feedback controller is designed as follows to track the set-point r [16].

$$u_0 = k_n \hat{y}^{(n-1)} + \ldots + k_1 (r - \hat{y}) \tag{11}$$

3.1 Extended State Observer (ESO)

An extended state observer estimates an unknown disturbance in addition to the states of the system.

As discussed in [12], each observer is characterized in terms of:

(1) Plant Description
(2) Inputs → Estimations
(3) Implementation

where, (1) provides the mathematical description of a process, (2) shows the inputs or the information required by the observer and its outputs or what estimations it produces, and (3) is implementation equations of the observer.

The ESO is designed to remove the requiremet of a precise model of the plant by rejecting unmodeled dynamics. This observer uses a simple canonical form and the unmodeled dynamics is included in the disturbance which has to be estimated [12].

The extended state observer is characterized as:

$$\begin{aligned} & y^{(n)} = f(x, t, u, w_f) + b_m u \\ & x = [y \quad \dot{y} \quad \ldots \quad y^{(n-1)}]^T \\ & ESO : \{u, y, n, b_m\} \to \{\hat{x}, \hat{f}\} \\ & [\dot{\hat{x}}_1 \quad \vdots \quad \dot{\hat{x}}_{n-1} \quad \dot{\hat{x}}_n \quad \dot{\hat{f}}]^T = \\ & [\hat{x}_2 \quad \vdots \quad \hat{x}_n \quad \hat{f} + b_m u \quad 0]^T + L(y - \hat{x}_1) \end{aligned} \tag{12}$$

As you can see in (12), a state called $\hat{f}$ is extended to n states of the system to estimate disturbance f .

A comprehensive survey of disturbance observers can be found in [12].

3.2 Generalized Extended State Observer (GESO)

R. Miklosovic et. al. in [17] modified the ESO to include derivative estimations of the disturbance and called it GESO. With this modification, the observer will estimate derivatives of disturbance in addition to the states of the system and disturbance.

The GESO is characterized as follows:

$$\begin{aligned} & y^{(n)} = f(x, t, u, w_f) + b_m u \\ & x = [y \quad \dot{y} \quad \ldots \quad y^{(n-1)}]^T \\ & z = [f \quad \dot{f} \quad \ldots \quad f^{(h-1)}]^T \\ & GESO : \{u, y, n, h, b_m\} \to \{\hat{x}, \hat{z}\} \\ & [\dot{\hat{x}}_1 \quad \cdots \quad \dot{\hat{x}}_{n-1} \quad \dot{\hat{x}}_n \quad \dot{\hat{z}}_1 \quad \cdots \quad \dot{\hat{z}}_{h-1} \quad \dot{\hat{z}}_h]^T = \\ & [\hat{x}_2 \quad \ldots \quad \hat{x}_n \quad \hat{f} + b_m u \quad \hat{z}_2 \quad \cdots \quad \hat{z}_h \quad 0]^T \\ & + L(y - \hat{x}_1) \end{aligned} \tag{13}$$

This observer estimates the derivatives of disturbance up to order *h*, that is determined in observer equations (13). In fact, *h* is the number of extended states to the system states in order to estimate disturbance and its derivatives. With *h=1*, the GESO estimates only the disturbance as ESO and with *h=2,3* and .... , estimates the first, second and higher derivatives of disturbance in addition to disturbance and the states of the system.

With This improvement, the observer has the ability to track higher order disturbances. The GESO with *h =1,2,3* can respectively track a square, triangular, or parabolic disturbance [17].

4. Designing LFC for a Three-Area Power System

In this section, we design an ADRC using GESO for the load-frequency control of the system under study. According to equations (5)and (6), for each area we can write:

$$\begin{aligned} Y_i(S) &= G_{p_i}(s)U_i(s)+d_i \\ d_i &= G_{tie_i}\Delta P_{tie_i} + G_{d_i}\Delta P_{L_i} \end{aligned} \tag{14}$$

And the transfer function of each area is of order three and in the form

$$\begin{aligned} G_{p_i}(s) &= \frac{b_0}{Den_P(s)} \\ Den_P(s) &= a_3 s^3 + a_2 s^2 + a_1 s + a_0 \end{aligned} \tag{15}$$

First, we must reform the plant model to the form of (7). The equation (14) can be written as

$$\begin{aligned} a_3 s^3 Y_i(S) = b_0 U_i(s) + \\ \left(-a_2 s^2 - a_1 s - a_0\right) Y_i(S) \\ + d_i . Den_P(s) \end{aligned} \tag{16}$$

or

$$s^3 Y_i(S) = bU_i(s) + f_i \tag{17}$$

where, f_i is the generalized disturbance of area #i defined as

$$f_i = \frac{1}{a_3}\left[\left(-a_2 s^2 - a_1 s - a_0\right)Y_i(S) + d_i . Den_P(s)\right] \tag{18}$$

and b is the high frequency gain given by:

$$b = b_0 / a_3 \tag{19}$$

Now, in order to estimate the generalized disturbance f and its derivative $\dot{f}$, we design a GESO as discussed in section 3.

According to equation (13), the GESO with $h = 2$ will be as follows:

$$\begin{aligned} &[\dot{\hat{x}}_1 \quad \dot{\hat{x}}_2 \quad \dot{\hat{x}}_3 \quad \dot{\hat{z}}_1 \quad \dot{\hat{z}}_2]^T = \\ &[\hat{x}_2 \quad \hat{x}_3 \quad \hat{z}_1 + b_m u \quad \hat{z}_2 \quad 0]^T \\ &+L(y - \hat{x}_1) \end{aligned} \tag{20}$$

where, $\hat{x}$ and $\hat{z}$ are the estimations of x and z respectively, which are defined in (21).

$$\begin{aligned} x &= [y \quad \dot{y} \quad \ddot{y}]^T \\ z &= [f \quad \dot{f}]^T \end{aligned} \tag{21}$$

In equation (20), L is the observer gain vector and is given by:

$$L = \left[\beta_1 \quad \beta_2 \quad \beta_3 \quad \beta_4 \quad \beta_5\right]^T \tag{22}$$

Hence, as discussed in (20) and (21) the state space representation of the observer is as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu + E\ddot{f} \\ y &= Cx \end{aligned} \tag{23}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ b \\ 0 \\ 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, C = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{24}$$

A choice is to locate all the eigenvalues of the ESO at $-\omega_0$. As discussed in [16] , for this purpose, the values of the elements of the vector L must be chosen as:

$$\beta_i = \binom{n+h}{i}\omega_0^i \qquad i = 1,2,\ldots,n+h \tag{25}$$

See [15], for more details on tuning the observer parameters.

If the observer gains are tuned such that the matrix $A - LC$ is Hurwitz, then $\hat{x}$ and $\hat{z}$ will track x and z respectively, and hence from (20) and (21) we can conclude that

$$z_4 \approx f \quad , \quad z_5 \approx \dot{f} \tag{26}$$

Now, according to equation (26), z_4 and z_5 are the estimations of the generalized disturbance f and its first derivative $\dot{f}$, respectively. Then, a state feedback controller must be designed as follows to reject the generalized disturbance, z_4, and track the set-point r.

$$\begin{aligned} u &= (u_0 - z_4)/b \\ u_0 &= k_1(r - z_1) + k_2 z_2 + k_3 z_3 \end{aligned} \tag{27}$$

As described in [16], the gains of the state feedback controller is chosen as:

$$k_i = \binom{n}{n+1-i}\omega_c^{n+1-i} \qquad i = 1,2,\ldots,n \tag{28}$$

where ω_c represents the bandwidth of the controller.

5. Simulation Results

A three-area power system model, which is shown in Fig. 1 is chosen to demonstrate the efficiency of the designed controller in section 4. The system parameters are given in TABLE 1.

With $\omega_o = 20$ and $\omega_c = 4$, from (25) and (28), the gains of generalized extended state observer and controller are obtained as:

$$\begin{aligned} L &= \left[5\omega_0 \quad 10\omega_0^2 \quad 10\omega_0^3 \quad 5\omega_0^4 \quad \omega_0^5\right]^T \\ k &= \left[\omega_c^3 \quad 3\omega_c^2 \quad 3\omega_c\right]^T \end{aligned} \tag{29}$$

In all simulations, the load disturbance is applied to the three areas at t = 1, 7, and 14 seconds respectively.

TABLE 1 : The Values of System Parameter

	T_{ij}	T_G	T_T	T_P	K_P	R	β
Area 1	0.5	0.08	0.3	20	120	2.4	0.4
Area 1	0.5	0.072	0.33	25	112.5	2.7	0.4
Area 1	0.5	0.07	0.35	20	115	2.5	0.4

5.1 Load Disturbance Rejection

As we mentioned before, the ADRC designed in [16] based on ESO, can only reject the step disturbance and have not a good performance for higher order disturbances. In order to show this, we first apply the controller designed in [16] to the three-area system with ramp disturbance. The responses of the three different areas are shown in the Fig. 2.

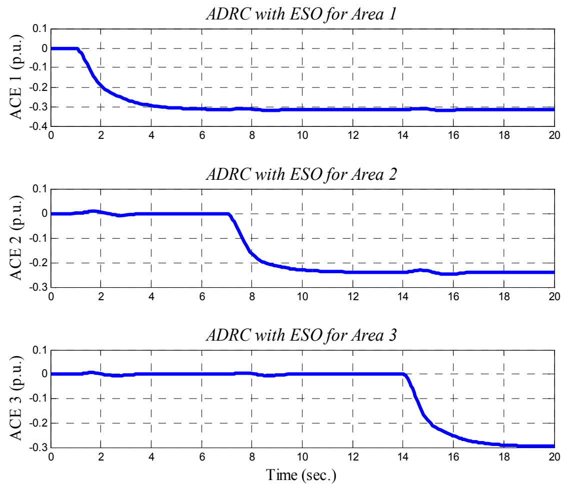

Fig. 2: responses of the ADRC with ESO designed in [16] to the system with ramp disturbance

As you can see, the controller cannot reject the disturbance and the area control error does not converge to zero in any area.

Now, the controller designed in section 4 is applied to the same system to demonstrate the ability of the proposed method to reject the high order disturbance.

the responses are shawn in Fig. 3.

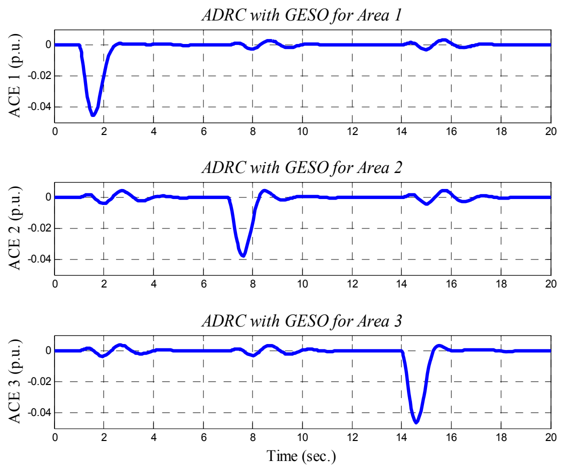

Fig. 3: responses of the ADRC with GESO designed in this paper to the system with ramp disturbance

It can be seen that the load disturbance is rejected by the proposed controller and the area control error converges also to zero in all areas.

5.2 Effect of Parameters Deviation

In order to investigate the robustness of the proposed controller against system parameters deviation, some of the system parameters are changed and the results are compared with the controlled system in [11] by IMC based PID. Fig. 4 and Fig. 5 show the results.

The changes applied to the system parameters are as follows:

$$K_{P_1(new)} = K_{P_1(nom)} + 50\% \qquad R_{1(new)} = R_{1(nom)} + 50\%$$

$$K_{P_2(new)} = K_{P_2(nom)} + 30\% \qquad R_{2(new)} = R_{2(nom)} + 30\%$$

$$K_{P_3(new)} = K_{P_3(nom)} + 20\% \qquad R_{3(new)} = R_{3(nom)} + 20\%$$

$$T_{ij\,(new)} = T_{ij\,(nom)} + 50\%$$

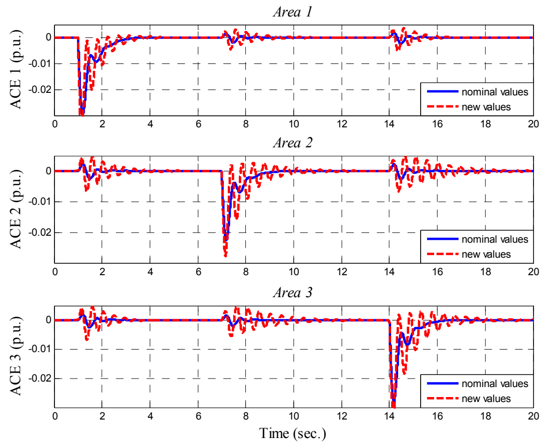

Fig. 4: effect of system parameters changes on the system controlled by IMC based PID designed in [7]

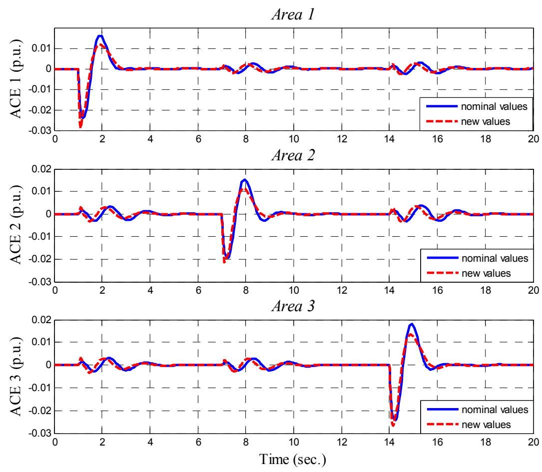

Fig. 5: effect of system parameters changes on the system controlled by ADRC designed in this paper

Fig. 4 and Fig. 5 show that the proposed controller in this paper is more robust to the system parameter deviations than the designed controller in [11]. Because, ADRC uses only two parameters of the system, one is the order of the plant n, and the other is the high frequency gain b defined in equation (19), but in the IMC based PID designed in [11], all the parameters of the transfer function of the system are needed to be known.

6. Conclusion

In this paper, a disturbance rejection control scheme is used for the load-frequency control of a multi-area power system. In this method, generalized extended state observer which is an improvement of the extended state observer is designed to estimate high order disturbances. The most important advantage of this method is that it need a little information about system model, which results in better robustness against variations of the system parameters.

Making the use of simulation, it has been demonstrated that the method has better performances in rejection of high order disturbances comparing simple extended observer. On the other hand, better robustness has been observed against model parameter changes in comparison with the internal model control based PID controller.

In real power systems, load disturbances are discontinuous but GESO has been designed linearly. Therefore, GESO cannot estimate discontinuous disturbances accurately. Consequently, nonlinear parts could be added to the observer, which makes this method a powerful tool for multi-area power systems.

On the other hand, the controller gain, which is considered as input data for the observer, is achieved from system model. If the gain is identified online and sent to observer, the observer and control system adapt themselves with changes in system parameters.

In addition, for practical situations power system limitations such as governor valve displacement limitations could be applied to the system.

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