LOAD FREQUENCY CONTROL OF POWER SYSTEMS WITH GOVERNOR DEAD-ZONE NONLINEARITY VIA ACTIVE DISTURBANCE REJECTION

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Abstract: *Actuator dead-zone is common in industrial control. However, while designing linear controllers, the actuator dynamics are usually assumed to be linear. Therefore, the dynamic performance degrades when there is governor dead-zone. In this paper, design and analysis of load frequency control for power systems with governor dead-zone via linear active disturbance rejection control (LADRC) is presented. In order to improve the performance of LADRC with governor dead-zone, two schemes are proposed to overcome the dead-zone nonlinearity, where the nonlinearity is estimated via the extended state observer (ESO) and rejected quickly in LADRC. Simulation results show that the proposed two schemes can achieve good control performance for power systems with governor dead-zone.*

Key words: *Load frequency control (LFC), governor dead-zone nonlinearity, linear active disturbance rejection controller (LADRC), extended state observer(ESO);*

1. Introduction

Controlling large interconnected power systems is one of the most challenging problems for controller designers. One of the most important control objectives in power systems for supplying sufficient and reliable electric power with quality is to control the output power of generating units. Frequency variations in interconnected power systems can cause serious instability problems. For stable operation, constant frequency and active power balance must be provided. To improve the stability of the power networks, it is necessary to design LFC systems that control the power generation and active power on tie-lines. Therefore, to ensure the power quality, a load frequency control (LFC) system is needed. The goal of LFC is to return the frequency to its nominal value and minimize unscheduled tie-line power flows between interconnected control areas.

Load Frequency Control (LFC) is one of the most importance issues in electric power system design and operation, and conventional LFC uses an integral controller. The high integral gain may deteriorate the system performance and cause large oscillations and instability. Thus, a lot of approaches have been reported to tune the gain of the integral controller.

With the increase in size and complexity of modern power systems, the risk that system oscillation might propagate into wide area resulting in a wide-area blackout is increased. So advanced control methods were applied in LFC, e.g., optimal control [1, 2]; variable structure control [3]; adaptive control [4]; and robust control [5,6], and PID control [7-10]..

Actuator dead-zone is common in industrial control. However, while designing linear controllers, the actuator dynamics are usually assumed to be linear. Therefore, the dynamic performance degrades when there is governor dead-zone. [11] proposed a gain scheduling PI controller for an Automatic Generation Control (AGC) system consisting of two-area thermal power system with governor dead-zone nonlinearity; [12] proposed a sliding control accounting for hardware limitation of mechanical actuators with dead-zone; [13] proposed a fuzzy two-degree-of-freedom controller and its application to the speed control of an induction motor drive; [14] proposed a motion control with dead-zone estimation and compensation using GRNN for TWUSM drive system; [15] studied stabilization of control systems with dead-zone nonlinearity of unknown characteristics; [16]

designed a dead-zone compensator of a DC motor system using fuzzy logic control (FLC).

Recently, an active disturbance rejection control (ADRC) method was applied to the LFC problem [17]. The method aims to reject the disturbance by providing its estimation through an extended observer, thus external disturbance can be rejected more quickly. However, the ADRC scheme has not considered system nonlinearities such as governor dead-zone. .

In this paper, load frequency control for power systems with dead-zone nonlinearity is studied. Two compensation schemes are proposed for linear active disturbance rejection controller (LADRC) to overcome the dead-zone nonlinearity for power systems with governor dead-zone. Simulation results show that the compensation scheme can improve the performance of the controlled system.

2 System model of LFC

Consider the case of a single generator supplying power to a single service area. The system can be adequately represented by the linear model shown in Fig. 1. The symbols are explained in table 1.

It is obvious that the plant LFC consists of three parts:

1) Governor with dynamics:

$$G_g(s) = \frac{1}{T_G s + 1}.$$

2) Turbine generator with dynamics:

$$G_t(s) = \frac{1}{T_T s + 1}.$$

3) Power systems with dynamics:

$$G_p(s) = \frac{K_P}{T_P s + 1}.$$

With the droop characteristics R, the system model can be expressed as

$$\Delta f = G(s)u + G_d(s)\Delta P_d \qquad (1)$$

where

$$G(s) = \frac{G_p G_t G_g}{1 + G_p G_t G_g / R},$$

$$G_d(s) = \frac{G_p}{1 + G_p G_t G_g / R}.$$

So LFC is a disturbance rejection problem: it uses feedback $u = -K(s)\Delta f$ to stabilize $G(s)$ under the load disturbance ΔP_d and meanwhile minimize the effect of ΔP_d on. Δf.
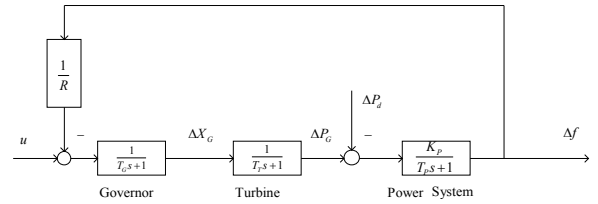

Fig. 1. Block diagram of single-area power system

Table 1
Nomenclature

ΔP_d	*Load disturbance(p.u.MW)*
K_P	*Electric system gain*
T_P	*Electric system time constant(s)*
T_T	*Turbine time constant(s)*
T_G	*Governor time constant(s)*
R	*Speed regulation due to governor action(Hz/p.u.MW)*
$\Delta f(t)$	*Incremental frequency deviation(Hz)*
$\Delta P_G(t)$	*Incremental change in generator output(p.u.MW)*
$\Delta X_G(t)$	*Incremental change in governor valve position*

3 Linear active disturbance rejection control

[18] first proposed active disturbance rejection control (ADRC) for rejecting disturbance of a nonlinear system in 1998. The scheme is to use an extended state observer (ESO) to estimate the disturbance of the system, and then try to reject it effectively using simple a control law. The scheme is similar to feedback linearization but it is much simpler in structure and applicable to a variety of

systems. However, the original nonlinear version of the ADRC has a lot of parameters to tune and thus hard to be applied in practice. [19] simplified the ADRC design procedure by considering its 'linear' version. The number of tuning parameters of LADRC is reduced to 2, stability and frequency response are applied to analyze the LADRC controlled system instead of manual tuning, thus help develop the LADRC idea and make it applicable to industry.

3.1 Structure of LADRC

Consider a generalized second-order system:

$$\ddot{y} = f(\dot{y}, y, \dot{u}, \omega, t) + bu \tag{2}$$

where y and u are output and input respectively, ω is the disturbance and b is a constant. The entire $f(\dot{y}, y, \dot{u}, \omega, t)$ is assumed to be unknown and denoted as the *generalized disturbance*, which is the combination of the unknown internal dynamics of the system and external disturbance.

In ADRC framework, the central idea is to estimate and cancel the unknown generalized disturbance $f(\dot{y}, y, \dot{u}, \omega, t)$. To do so, an extended state observer (ESO) is used. Let

$$z_1 = y, z_2 = \dot{y}, z_3 = f(\dot{y}, y, \dot{u}, \omega, t) \tag{3}$$

Assume that $f(\dot{y}, y, \dot{u}, \omega, t)$ is differentiable and let $f(\dot{y}, y, \dot{u}, \omega, t) = h$. The augmented model of (2) can be written as

$$\begin{cases} \dot{z} = Az + Bu + Eh \\ y = Cz \end{cases} \tag{4}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ b \\ 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \tag{5}$$

The state space observer, here, denoted as the Extended State Observer (ESO) is constructed as

$$\begin{cases} \dot{\hat{z}} = A\hat{z} + Bu + L(y - \hat{y}) \\ \hat{y} = C\hat{z} \end{cases} \tag{6}$$

where L is the observer gain vector

$$L = \begin{bmatrix} \beta_1 & \beta_2 & \beta_3 \end{bmatrix}^T \tag{7}$$

which can be obtained using any known method such as the pole placement technique. $\beta_1, \beta_2, \beta_3$ are the parameters of the ESO, $\hat{z}_1, \hat{z}_2, \hat{z}_3$ approach $y, \dot{y}$ and $f(\dot{y}, y, \dot{u}, \omega, t)$ respectively if the observer

gain L is chosen properly, thus the generalized disturbance f is available for control.

If we choose the control law as

$$u = \frac{-\hat{z}_3 + u_0}{b} \tag{8}$$

Then the original plant (2) becomes

$$\ddot{y} = f(\dot{y}, y, \dot{u}, \omega, t) - \hat{z}_3 + u_0 \tag{9}$$

If the ESO is properly designed, i.e. $\hat{z}_3 \approx f(\dot{y}, y, \dot{u}, \omega, t)$, then the original plant is reduced to be a simple double-integral system
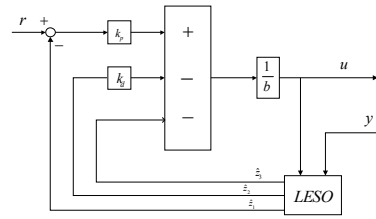
$$\ddot{y} \approx u_0 \tag{10}$$

Fig. 2. Block diagram of 2nd-order LADRC

Finally, the system can be easily controlled with a PD (Proportional-Derivative) controller

$$u_0 = k_p(r - \hat{z}_1) - k_d\hat{z}_2 \tag{11}$$

where r is the set point, k_p and k_d are control parameters. The structure of LADRC is shown in Fig. 2.

3.2 Parameter tuning

Let

$$K = \begin{bmatrix} K_p & K_d & 1 \end{bmatrix} / b \tag{12}$$

Then an LADRC has two sets of gains to tune: L, the observer gain for LESO, and K, the controller gain for double integral plant. For practical reason, tuning of these two gains is reduced to tuning parameters as suggested in [19]: w_c is the

controller bandwidth, and w_o is the observer bandwidth.

Consider the LESO, the transfer function from f to $\hat{z}_3$ is

$$\frac{\hat{z}_3}{f} = \frac{\beta_3}{s^3 + \beta_1 s^2 + \beta_2 s + \beta_3} \tag{13}$$

In order to place all the eigen-values of the ESO at $-\omega_o$, the observer gains are chosen as

$$\begin{cases} \beta_1 = 3\omega_o \\ \beta_2 = 3\omega_o^2 \\ \beta_3 = \omega_0^3 \end{cases} \tag{14}$$

that makes ω_o the only observer parameter to be tuned. Here, ω_o is denoted as the bandwidth of the observer.

Similarly, in order to simplify controller parameters, the bandwidth of the controller, denoted as ω_c, is introduced. Assume that all the closed-loop poles of the PD controller are placed at $-\omega_c$, and then the controller gains in (11) are given by

$$\begin{cases} k_d = 2\omega_c \\ k_p = \omega_c^2 \end{cases} \tag{15}$$

4 Load frequency control design with dead-zone

The model of single-area power system is shown in Fig. 1. In the actual system, there are nonlinear characteristics in the steam turbine governor, e.g., saturation, hysteresis, and dead-zone. The nonlinear characteristics will deteriorate the system performance. This phenomenon can be verified from the following example.

Example 1 Considering a single-area power system with the following parameters [10]:

$$K_P = 120, T_P = 20, T_T = 0.3, \\ T_G = 0.08, R = 2.4. \tag{16}$$

The system is controlled by a 2nd-order LADRC with the following parameters:

$$b = 5.5, w_c = 45, w_o = 1.1 \tag{17}$$

A step load $\Delta P_d = 0.01$ is applied to the system at $t = 1$, and the responses of the system are shown in Fig- 3 with and without dead-zone nonlinearity. It is observed that the control performance is degraded a lot with dead-zone=0.1.
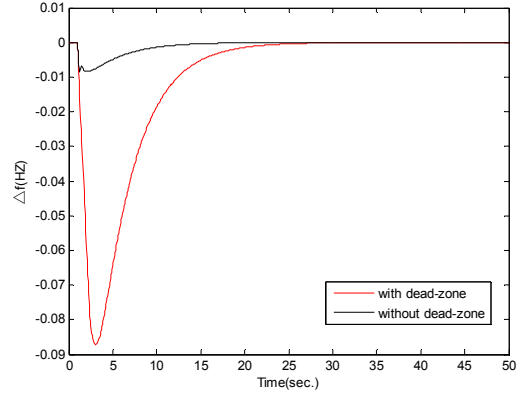

Fig. 3. The responses of power system under LADRC in LFC system

In order to overcome the effect of dead-zone, we will propose two compensation schemes.

4.1 Observer-based scheme

Note that LADRC has an observer-based feedback structure, the nonlinear characteristics will deteriorate the control performance because the controller state cannot be accurately estimated, thus we can overcome the effect if the controller state can be accurately estimated. Note that the observer of LADRC is exasperated and cannot be accurately estimated because of the governor dead-zone. Therefore, if only the nonlinear part of the governor feeds back to ESO, the problem because of the governor nonlinearity can be solved, and then the effect of the governor dead-zone is overcome. At the moment, the scheme is shown in Fig. 4, and $\tilde{N}$ represents the static nonlinear of governor.
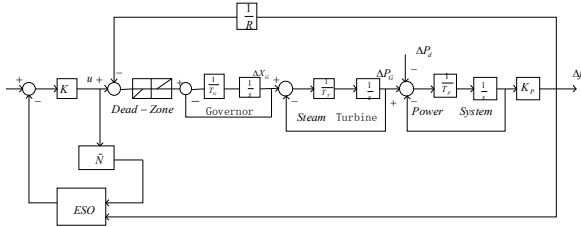
Fig. 4. Block diagram of observer-based scheme for LADRC in LFC system

To the show the performance of the LADRC with compensation scheme, a step load $\Delta P_d = 0.01$ is applied to the system at $t = 1$, and the responses of the system are shown in Fig. 5. It is observed that the control system cannot return to set value for a long time, and control performance is degraded a lot with dead-zone. However, when using the compensation scheme, the control system can quickly return to set point, and control performance can significantly improved. Therefore, we can overcome the effect of dead-zone using the compensation scheme.
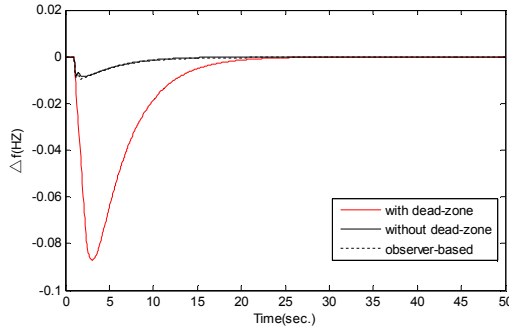
Fig. 5. The responses of power system under LADRC with the observer-based scheme

4.2 Error-compensation-based scheme

The observer-based scheme is easy to implement. However, the scheme must know the exact nonlinearity of the dead-zone, and it lacks some degree of freedom. Therefore, in this paper, another scheme is proposed for LADRC to overcome the dead-zone nonlinearity. The scheme is shown in Fig. 6, where the error of actual output of governor and

theoretical output of controller is added into ESO as an external disturbance for estimation and it can be used in the feedback control to reject quickly.
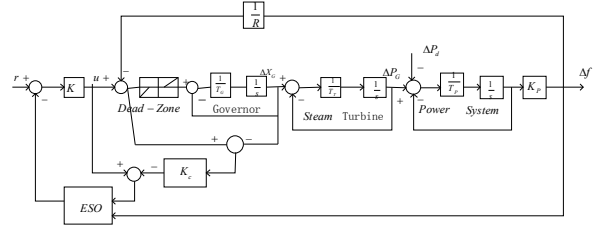

Fig. 6. Block diagram of error-compensation-based scheme for LADRC in LFC system

Using the error-compensation-based scheme, K_c is a static compensation coefficient, the system is controlled by a 2nd-order LADRC with the following parameters:

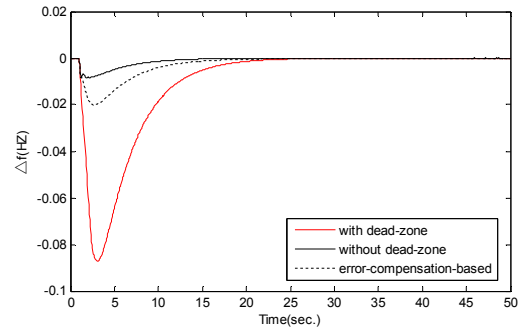$$K_c = 0.85, b = 5.5, w_c = 45, w_o = 1.1 \qquad (18)$$

Fig. 7. The responses of power system under LADRC with the error-compensation-based scheme

To the show the performance of the LADRC with compensation scheme, a step load $\Delta P_d = 0.01$ is applied to the system at $t = 1$, and the responses of the system are shown in Fig. 7. It is observed that the control system can faster return to set point, and control performance can significantly improved. Thus we can overcome the effect of dead-zone using the error-compensation-based scheme for LADRC in LFC system, and the scheme is practical and effective.

According to the proposed schemes and the effect, the following information is obtained:

1) The observer-based scheme can be adopted if the form and parameters of static nonlinear of governor is known.

2) One drawback of the observer-based scheme is that there are no adjustable parameters, so the error-compensation-based scheme may be used if it is needed. The scheme is to put the error of actual output of governor and theory output of controller into ESO, the error is eliminated using the aid of ESO, and the control performance is also improved. However, because the error-compensation-based scheme needs a static compensation coefficient, thus this parameter needs to be manually adjusted to avoid the instability of ESO.

5 Two-area extension

The LADRC for the load frequency control of a multi-area power system is readily extended. The load frequency control problem for multi-area power systems requires that not only the frequency deviation of each area must return to its nominal value but also the tie-line power flows must return to their scheduled values. So a composite variable, the area control error (ACE), is used as the feedback variable to ensure the two objectives. For simplicity, consider load frequency control for two areas. The model is shown in Fig. 8.

All symbols are similar to Fig. 1, except that T_{12} is the synchronizing power coefficient, a_{12} is the ratio of base power of area1 to that of area2, and ΔP_{tie} is the departure from the scheduled tie-line exchange power,

$$\Delta P_{tie} = \frac{T_{12}}{s}\left(\Delta f_1 - \Delta f_2\right), a_{12} = -1. \qquad (19)$$

B_1 and B_2 are frequency bias settings, and ACE_1 and ACE_2 are area control errors defined by

$$ACE_1 = \Delta P_{tie} + B_1 \Delta f_1, \qquad (20)$$
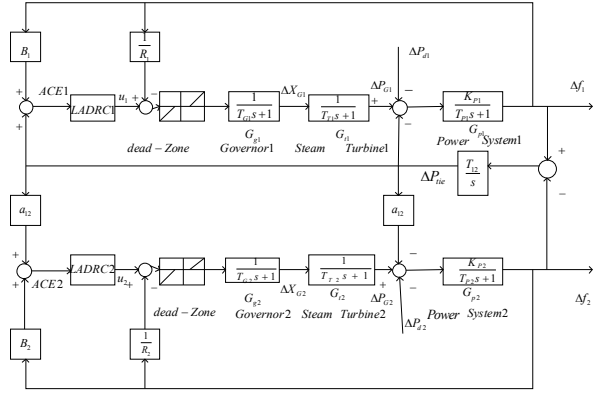$$ACE_2 = -\Delta P_{tie} + B_2 \Delta f_2$$

Fig. 8. Block diagram of LFC of two-area power system with governor dead-zone

From Fig.8, a 2×2 model from u_i to $ACE_i \left(i = 1, 2 \right)$ can be obtained:

$$\begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} = \begin{bmatrix} B_1 + \dfrac{T_{12}}{s} & -\dfrac{T_{12}}{s} \\ -\dfrac{T_{12}}{s} & B_2 + \dfrac{T_{12}}{s} \end{bmatrix} \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \end{bmatrix} \qquad (21)$$

and

$$\begin{bmatrix} \Delta f_1 \\ \Delta f_2 \end{bmatrix} = \begin{bmatrix} 1 + \dfrac{G_{p1}G_{t1}G_{g1}}{R_1} + \dfrac{G_{p1}T_{12}}{s} & \dfrac{-G_{p1}T_{12}}{s} \\ \dfrac{-G_{p2}T_{12}}{s} & 1 + \dfrac{G_{p2}G_{t2}G_{g2}}{R_2} + \dfrac{G_{p2}T_{12}}{s} \end{bmatrix}^{-1}$$
$$\times \begin{bmatrix} G_{p1}G_{t1}G_{g1} & 0 \\ 0 & G_{p2}G_{t2}G_{g2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \qquad (22)$$

A decentralized controller can be tuned assuming that there is no tie-line exchange power, i.e., $T_{12} = 0$. In this case

$$\begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} = \begin{bmatrix} B_1 \dfrac{G_{p1}G_{t1}G_{g1}}{1 + G_{p1}G_{t1}G_{g1}/R_1} & 0 \\ 0 & B_2 \dfrac{G_{p2}G_{t2}G_{g2}}{1 + G_{p2}G_{t2}G_{g2}/R_2} \end{bmatrix}$$
$$\times \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \qquad (23)$$

Thus load frequency controller for each area can be designed independently, and the LADRC design discussed for the single-area power system is readily applied to multi-area case. However, since there is

coupling among areas, the design for each area should take this into consideration. The robustness of the closed-loop system against the tie-line operation should be checked as proposed in [20].
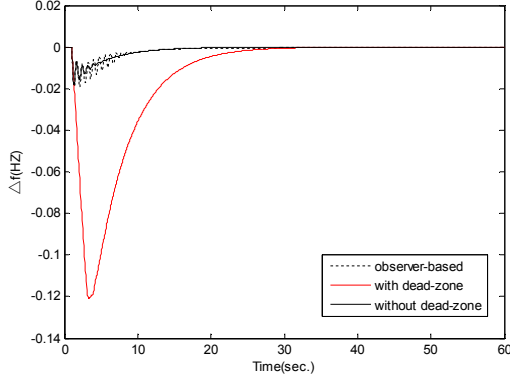
(a) Frequency deviation at AREA 1
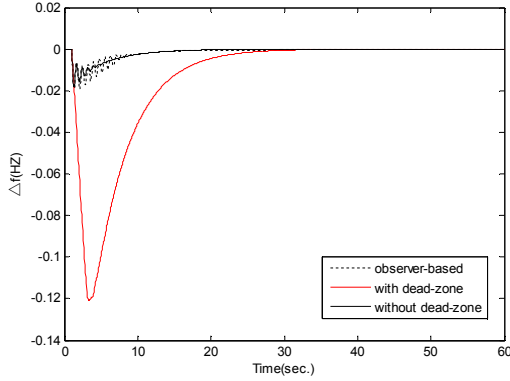
(b) Frequency deviation at AREA 2

Fig. 9. The responses of two-area power system under LADRC with the observer-based scheme

Example 2 Considering a two-area power system, for simplicity, the two areas are assumed to be identical, and the model parameters are:

$$T_{G1} = T_{G2} = 0.08, T_{T1} = T_{T2} = 0.3, \\ T_{P1} = T_{P2} = 20, K_{P1} = K_{P2} = 120, \\ R_1 = R_2 = 2.4. \tag{24}$$

The frequency bias settings are $B_1 = B_2 = 0.425$, and the synchronizing power coefficient is $T_{12} = 0.545$. Using the observer-based scheme, the following parameters of LADRC for two areas are:
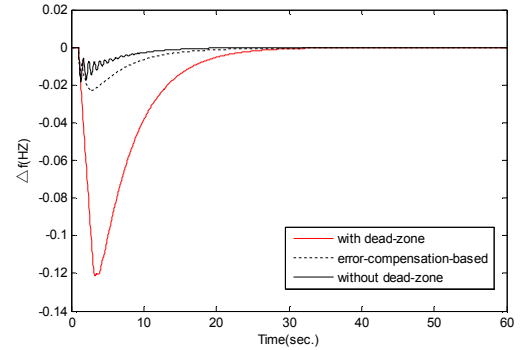
$$b_1 = b_2 = 9.5, w_{c1} = w_{c2} = 65, \\ w_{o1} = w_{o2} = 1.35 \tag{25}$$

Using the error-compensation-based scheme, the following parameters of LADRC for two areas are:

$$K_{c1} = K_{c2} = 0.9, b_1 = b_2 = 8.8, \\ w_{c1} = w_{c2} = 60, w_{o1} = w_{o2} = 1.3 \tag{26}$$
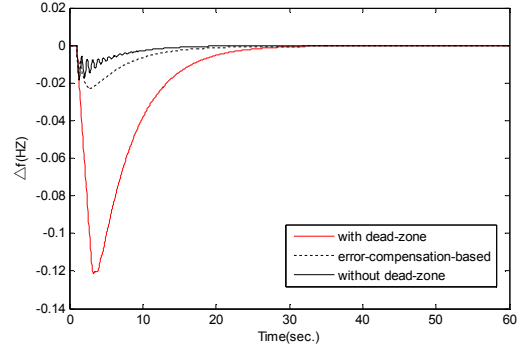
(a) Frequency deviation at AREA 1

(b) Frequency deviation at AREA 2

Fig. 10. The responses of two-area power system under LADRC with the error-compensation-based scheme

To the show the performance of the decentralized LADRC, the step load $\Delta P_{d1} = \Delta P_{d2} = 0.01$ are applied to the system at $t = 1$, and the responses of the system are shown in Figs. 9-10. It is observed that the control system cannot return to set point for a long time, and control performance is degraded a lot with dead-zone=0.1. However, when using the

two compensation schemes, the control system can quickly return to set point, and control performance can significantly improved. Therefore, we can overcome the effect of dead-zone using the two compensation schemes.

6 Conclusion

In this paper, design and analysis of load frequency control for power systems with governor dead-zone via linear active disturbance rejection control (LADRC) is presented. In order to improve the performance of LADRC with governor dead-zone, two schemes for overcoming the dead-zone nonlinearity are proposed, where the nonlinearity is estimated via the extended state observer (ESO). One is used to estimate the controller states, the other is to estimate the error of actual output of governor and theoretical output of controller. Simulation results show that the two schemes are practical and effective.

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