ANALYSIS AND DESIGN OF POWER SYSTEM WITH NONLINEARITY VIA ACTIVE DISTURBANCE REJECTION

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In the actual industrial control, the governor dead-band nonlinearity and the steam turbine generation rate constraint (GRC) are ubiquitous. The control performance of the system can be affected, and even unstable because of the nonlinearities. Therefore, a design of load frequency control (LFC) of power systems with governor dead-band nonlinearity and steam turbine GRC via linear active disturbance rejection control (LADRC) is presented. And then, a method of governor dead-band converted into the transfer function form is also proposed, the purpose of the method is to reduce the difficulty of parameter tuning. Further, an error compensation scheme is proposed for LADRC, while maintaining the own characteristics of LADRC, the scheme can eliminate the effect of governor dead-band nonlinearity and steam turbine GRC effectively. Simulation results show that the error compensation scheme based on LADRC can recover and improve the performance of the controlled system effectively. The method is feasible and effective.

**Keywords:** load frequency control; governor dead-band nonlinearity; error compensation scheme; generation rate constraint; linear active disturbance rejection control

1. Introduction

Frequency stability is an important control objective in power system. For interconnected power systems, nevertheless, any change in load may cause deviations in the exchange power of the inter-system tie lines as well as fluctuations in the system frequency and may even lead to system instability. Therefore, in order to solve the problem and guarantee power quality, there must be a load frequency control (load frequency control, LFC) system. The purpose of designing this system is to maintain the system frequency at the nominal value so that exchange power of the unplanned tie line between the control areas is minimal [1].

An important issue in the design and operation of power systems is that conventional LFC only adopts integral control. It is however generally known that bigger integral gain will worsen the system performance, causing big system

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oscillations and even instability. Hence, integral gain must be set by compromising between the ideal transient recovery response of the system and a small overshoot. So far, a variety of methods for setting LFC integral gain have been proposed in the existing literatures [2].

With the increasing scale and complexity of modern power systems, there is increasing risk of wide-area power outages caused by system oscillations. Therefore, a variety of advanced control methods have been proposed in the existing literature to solve the LFC issue. A new PID (proportional-integral-derivative) debugging method is proposed to solve the LFC issue [3]; the bacterial foraging optimization algorithm is used to debug PI (proportional-integral) controller, thereby improving control performance of the two-region power system [4]; a PID setting process based on two-degree-of-freedom (TDF) internal model control (IMC) is mentioned [5]; a fuzzy C-means clustering technique (FCM) is used to generate the optimal fuzzy rule, and the phase plane input by the fuzzy controller is used to derive its rules [6]. Most of these literatures assume that the system is linear when designing the required controller. However, in actual control, some non-linear characteristics are widespread, such as: governor dead band and power generation rate constraints (GRC). When these nonlinear characteristics present in the system, the controllers designed in these literatures cannot provide effective and reliable control. On the premise of governor dead band and GRC in the LFC system, this paper designs controller that guarantees control performance of the system.

In recent years, some literatures have studied nonlinear characteristics of LFC systems. A sliding mode control is used to solve the hardware limitation caused by the actuator dead band [7]; the generalized regression neural network (GRNN) is used to estimate and compensate the dead band, thereby improving control performance of the travelling wave ultrasonic motor (TWUSM) drive system [8]; a robust multi-variable model predictive control (MPC) method is used to solve LFC problem of multi-region power systems. The control strategy takes into account GRC and multi-variable nature of LFC [9]. Gravitational search algorithm (GSA) and pattern search (PS) method are employed to analyze LFC problem of multi-region power systems [10]; a gain scheduling PI controller method is applied to two-region automatic generation (AGC) control system with a governor dead band[11]; the type 2 fuzzy controller design method different from conventional controllers and type 1 fuzzy controllers is used to solve GRC [12] problem of the two-region reheat thermal power generation system; a stability equation method is used to design and analyze interconnected power system with governor dead band [13]. This method takes into account non-linear effects in the design phase. Targeting at the presence of governor dead band or GRC in LFC systems, these literatures propose a variety of control strategies for solution, and adopt various algorithms for optimization and setting. However, the
designed controller has relatively complex structure and big calculation amount, so industrial application is difficult. Targeting at LFC system with governor dead band and GRC, this paper adopts a control method: linear active disturbance rejection control (LADRC) [14]. Compared with other control approaches, this method has a simpler structure and is applicable to various nonlinear systems. The controller only requires setting of two parameters, which is easy to set and simple in calculation, so industrial application is easy.

In actual industrial control, governor dead band and GRC are universal. These non-linear factors will affect system control performance and even cause instability. Therefore, this paper applies LADRC to LFC system with governor dead band and GRC. It also proposes to convert governor dead band into the form of transfer function, thereby reducing the difficulty of LADRC parameter setting. Then, based on this, this paper proposes an error compensation strategy that enables LADRC to further improve its control performance while maintaining the active disturbance rejection characteristics. Thus, the effect of the governor dead band and GRC on the system can be well eliminated. Moreover, the compensation strategy is simple in design and easy to apply.

The rest of the paper is arranged as follows: the first part designs a single-region power system with governor dead band and GRC; the second part proposes LADRC design method; the third part illustrates control of LFC system with governor dead band and GRC using LADRC, and proposes LADRC-based error compensation strategy. Finally, the fourth part is a conclusion of the work of this paper.

2. LFC system model

The single-region power system model with governor dead band and GRC discussed in this paper is shown in Fig. 1. Where $\Delta P_d$ represents load disturbance, $R$ is governor speed adjustment constant, $K_p$ is generator gain, $T_p$, $T_r$ and $T_g$ are generator time constant, steam turbine time constant and governor time constant, $\Delta f(t)$ is frequency deviation, $\Delta P_i(t)$ indicates output changes of the steam turbine, $\Delta X_g(t)$ represents position changes of the governor valve.

In the model shown in Fig. 1, a governor dead band acts on the control zone to simulate nonlinearity. The governor dead band has a great impact on the dynamic performance of the power system. In a more practical analysis: governor dead band must be considered when analyzing nonlinear characteristics of the system. Due to the governor dead band, the speed will be increased or decreased before the valve position changes, causing system
oscillations. It tends to produce a continuous sinusoidal oscillation with a natural period of \( T_0 = 2s \), that is, a frequency oscillation of \( f_o = 0.5Hz \).

The governor dead band in this area is indicated by descriptive function method, which is used to linearize the governor dead band. The dead band nonlinearity is defined as \( e = F(m, \omega) \). In the above equation, \( m \) is considered as sinusoidal oscillation caused by the frequency oscillation of \( 0.5Hz \), whose expression is: \( m = A_1 \sin(2\pi f_o t) \). As this dead-band nonlinearity tends to produce continuous sinusoidal oscillations, the function \( F \) can be viewed as a Fourier series as follows:

\[
F(m, \omega) = F_0 + K_1 m + \left( K_2 / 2\pi f_0 \right) \left( dm/dt \right) + L
\]  

(1)

In the above equation, it is sufficient to only consider the first three terms while ignoring the fourth and higher order terms. When the dead band nonlinearity is symmetrical about the origin, the value of \( F_0 \) is 0. If the dead band value is 0.0005, the Fourier coefficients can be obtained: \( K_1 = 0.8 \) and \( K_2 = -0.2 \). Then, non-linear transfer function of the governor dead band can be expressed as follows [11]:

\[
G_m = \left( 0.8 - 0.2s/\pi \right) / (1 + T_m s)
\]  

(2)

Therefore, in this paper, the governor dead band nonlinearity is represented in the power system model in the form shown in Fig. 2.
Analysis and design of power system with nonlinearity via active disturbance rejection

In 1998, Professor Han Jingqing of the Chinese Academy of Sciences first proposed to apply active disturbance rejection control (ADRC) to anti-interference problem solving of nonlinear systems [15]. The idea is to estimate the system disturbance using an extended state observer (ESO), and then use simple control for suppression. Similar to feedback linearization, this idea is simpler in structure and is adaptable to various nonlinear systems. Nonetheless, since non-linear ADRC requires adjustment of multiple parameters, it is limited in practical applications. American scholar Gao Zhiqiang simplified the original non-linear ADRC to a linear form and proposed a linear ADRC. The controller only requires setting of two parameters in the end, which greatly simplifies the ADRC setting process, making its industrial application possible.

LADRC does not require complete model of the controlled object or disturbance, but only requires the relative order and gain of the object. It is assumed that the controlled system has the following model:

\[
y(t) = bu(t) + f(y(t), u(t), d(t))
\]

Where, \(f(y, u, d)\) is a combination of unknown system dynamics and external disturbances. The assumption in the LADRC design is unknown, which is referred to as generalized perturbation. Let

\[
z_1 = y, z_2 = \dot{z}_y, z_r = y^{(r-1)}, z_{r+1} = f(y, u, d)
\]

Assume that \(f(y, u, d)\) is differentiable and \(\dot{z}_y = h(t)\), then the system model (3) can be written as

\[
\begin{align*}
\dot{z} &= Az + Bu + Eh \\
y &= Cz
\end{align*}
\]

3. Linear ADRC control

Fig. 2. Single-region power system with governor dead band and GRC

where:

\[
\begin{align*}
\Delta y &= \Delta \frac{1}{R} + \Delta \frac{0.2 \pi t + 0.8}{T_s + 1} \\
\Delta \frac{1}{R} &= \Delta \left[\frac{1}{T_s} \text{ turbine}\right] \\
\Delta \frac{1}{R} &= \Delta \left[\frac{1}{T_s} \text{ GRC}\right] \\
\Delta f &= \Delta \frac{\kappa_s}{T_s + 1} \text{ power system}
\end{align*}
\]
According to the principles of modern control theory, linear extended state observer (LESO) is defined as:

\[
\dot{\hat{z}} = A\hat{z} + Bu + L(y - \hat{y})
\]

(6)

Where, \(\hat{z}\) is the estimated value of \(z\), \(L\) represents the gain matrix of the state observer, which controls accuracy of the estimated value. By pole configuration, it is obtained that:

\[
L = [\beta_1, \beta_2, L, \beta_r, \beta_{r+1}]^T
\]

(7)

When \(A - LC\) asymptotically stabilizes, \(\hat{z}_i(t), L\), \(\hat{z}_r(t)\) and \(z_{r+1}\) approach to \(y(t), L\), \(y^{(r)}(t)\) and generalized perturbation \(f(y,u,d)\), which means that this perturbation estimate can be used for control, so that faster suppression is possible.

In the LADRC framework, the main idea is to estimate the unknown generalized perturbation \(f(y,u,d)\) through a LESO. If the following control law is taken:

\[
u(t) = -\frac{\hat{z}_{r+1}(t) + u_0(t)}{b}
\]

(8)

Then, the controlled system (3) becomes

\[
y^{(r)}(t) = f(y,u,d) - \hat{z}_{r+1}(t) + u_0(t)
\]

(9)

When LESO is designed properly, there is \(\hat{z}_{r+1}(t) \approx f(y,u,t)\) so that the system becomes a multiple integral system of \(r\):

\[
y^{(r)}(t) \approx u_0(t)
\]

(10)

Finally, the system adopts the following state feedback control law for control:

\[
u_0(t) = -k_1y(t) - k_2\hat{y}(t) - L - k_r y^{(r-1)}(t)
\]

(11)
Since \( \hat{z}_i(t)L\), \( \hat{z}_i(t) \) approaches \( y(t)L\), \( y^{(r)}(t) \), the final control law is approximated as
\[
u(t) = k_1 \hat{z}_i(t) + L + k_r \hat{z}_r(t) + \hat{z}_{r+1}(t) = -K \hat{z}
\]
(12)

Where
\[
K = [k_1 k_2 L k_r 1] / b
\]
(13)

As can be seen, two sets of parameters need to be designed for a LADRC: the observer gain \( L \) of LESO and state feedback gain \( K \) of \( r \) multiple integral system. To facilitate adjustment, these two sets of gain settings can be converted into two parameter settings: the controller bandwidth \( w_c \) and the observer bandwidth \( w_o \).

Since control performance of general controllers has a direct relationship with bandwidth, the accuracy of LESO estimate value has a great correlation with its bandwidth. Considering LESO, characteristic equation of \( A - LC \) is
\[
|sI - (A - LC)| = s^{r+1} + \beta_s s^r + L + \beta_{r+1}
\]
(14)

For simplicity, assume that all observer poles are configured at \(-w_o\), then:
\[
s^{r+1} + \beta_s s^r + L + \beta_{r+1} = (s + w_o)^{r+1}
\]
(15)

Therefore
\[
\beta_i = \binom{r+1}{i} w_o^i, i = 1, L, r + 1
\]
(16)

Hence, the observer gain only requires adjustment of single parameter \( w_o \), making the calculation simple. In general, LESO estimation accuracy is higher when \( w_o \) is bigger. However, it also makes the observer more sensitive to noise. Accordingly, selection of \( w_o \) should be balanced between control performance and anti-noise performance. During the actual parameter setting, \( w_o \) should be gradually increased from a small value until it meets performance requirements. After \( w_o \) is determined, the corresponding \( \beta_i \) value can be determined according to formula (16).

When the generalized perturbation \( f(y,u,d) \) can be accurately estimated, the original system becomes a multiple integral model, and when \( \hat{z}_i(t)L, \hat{z}_i(t) \) approximate \( y(t)L, y^{(r)}(t) \), the state feedback closed-loop characteristic equation is:
\[
|sI - (A - BK)| = s(s^r + k_a s^{r-1} + L + k_2 s + k_1)
\]
(17)
Similarly, for simplicity, all controller poles (except the origin) can be configured at \(-w_c\):

\[
s' + k_w s^{-1} + L + k_2 s + k_i = (s + w_c)^r
\]

Hence

\[
k_i = \left(\frac{r}{i-1}\right) w_c^{n-i+1}, i = 1, L, r
\]

The feedback control law gain thus only requires adjustment of a single parameter \(w_c\). Generally, for a bigger \(w_c\), system response is faster, but there is certain effect on performance stability.

LADRC is a universal control structure independent of the controlled object model. It requires awareness of the relative order \(r\) and the corresponding gain \(b\). In particular, LADRC only requires setting of 2 parameters, so it is easy for control engineer to understand. In addition, the structure comes with integration behavior, so there is no need to add an integrator in the design.

4. Simulation analysis

Fig. 3. LADRC with error compensation strategy

The single-region system model discussed herein is shown in Fig. 2. In practical systems, governor dead band and GRC are widespread. These non-linear characteristics will degrade the system control performance and even cause instability. In this paper, LADRC is applied to LFC system with these
nonlinear characteristics to restore and improve the system control performance. Then, this paper proposes an error compensation strategy to further improve system control performance while maintaining active disturbance rejection characteristics of LADRC, so that the impact of these nonlinear characteristics on the system can be well eliminated. The compensation strategy is shown in Fig.3. The idea is to take the error between the theoretical output and actual output of the steam turbine as an external disturbance and estimate it with LESO, so that LADRC can eliminate the effects of governor dead band and GRC, and the system control performance can be quickly restored and improved. Where, $k$ is a manually adjustable static compensation coefficient.

Example: To verify the effect of the governor dead band and GRC on LFC system and the effect of LADRC-based error compensation strategy, the single-region power system with the following parameters is considered [5]:

$$K_p = 120, T_p = 20, T_f = 0.3,$$
$$T_g = 0.08, R = 2.4$$  \tag{20}

It adopts 3rd order LADRC for control, and its parameters are selected as follows:

$$b = 120, w_c = 2.2, w_o = 25$$  \tag{21}

The compensation coefficient is $k = 0.7$. To show the LADRC control effect after adoption of this compensation strategy, when $GRC = 0.0017$ MW/s and the dead band value is 0.0005, a step signal $\Delta P_0 = 0.01 (t = 1s)$ is added. The system response curve is shown in Fig. 4. The solid red line indicates the situation where error compensation strategy is not adopted in the system. The black dotted line indicates the situation where error compensation strategy is adopted in the system. Obviously, when the error compensation strategy is not adopted, the system control performance is deteriorated and becomes unstable due to the presence of governor dead band and GRC. After adoption of error compensation strategy, the system control performance is well improved. Hence, this compensation strategy is effective in eliminating governor dead band and GRC. In addition, the compensation strategy has a manually adjustable static compensation coefficient $k$. As the compensation coefficient increases, the system control performance is better, but system instability is also possible. When it gradually increases to 1.35, the system becomes unstable, and the simulation results are shown in Fig. 5.
Fig. 4. LADRC power system step response using error compensation strategy ($k = 0.7$)

Fig. 5. LADRC power system step response using error compensation strategy ($k = 1.35$)
5. Conclusion

(1) By applying LADRC method to LFC system with governor dead band and GRC, the designed controller has a simple structure and is easy to calculate.

(2) It is proposed to transform the governor dead band into a transfer function form, which can reduce the difficulty in setting LADRC parameters.

(3) A LADRC-based error compensation strategy is proposed. Simulation results prove that the governor dead band and GRC effects on the system can be well eliminated, so that the system control performance can be quickly restored and improved.

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