U.P.B. Sci. Bull., Series C, Vol. 82, Iss. 2, 2020 ISSN 2286-3540

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

Shancheng QI[1], Shuaibing CHANG[1], Bin ZHAO[1], Menggao LI[2]

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

[1] School of Electrical Engineering and Automation, Henan Institute of Technology, China
[2] State Power Investment Corporation Xinxiang Yuxin Power Generation Co., Ltd., China

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, ΔP_d represents load disturbance, R is governor speed adjustment constant, K_P is generator gain, T_P, T_T and T_G are generator time constant, steam turbine time constant and governor time constant, $\Delta f(t)$ is frequency deviation, $\Delta P_G(t)$ 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 $f_o = 0.5Hz$.

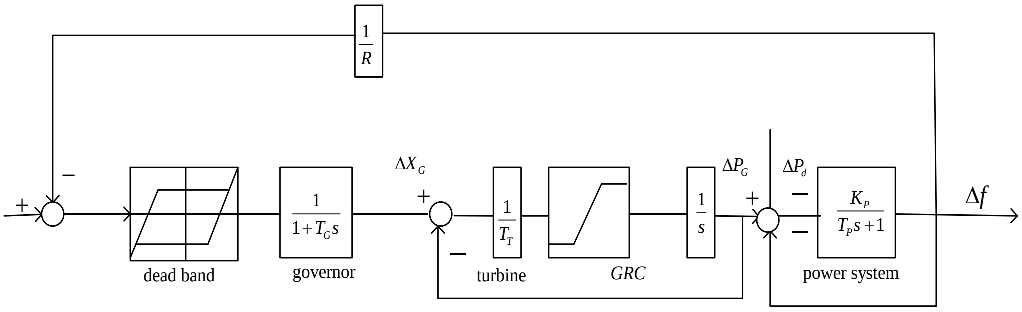

Fig. 1. Single-region power system with governor dead band and GRC

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 $e = F(m, \dot{m})$. 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:

$$F(m, \dot{m}) = F_0 + K_1 m + (K_2 / 2\pi f_0)(dm/dt) + \cdots \tag{1}$$

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]:

$$G_m = (0.8 - 0.2s/\pi) / (1 + T_m s) \tag{2}$$

Therefore, in this paper, the governor dead band nonlinearity is represented in the power system model in the form shown in Fig. 2.

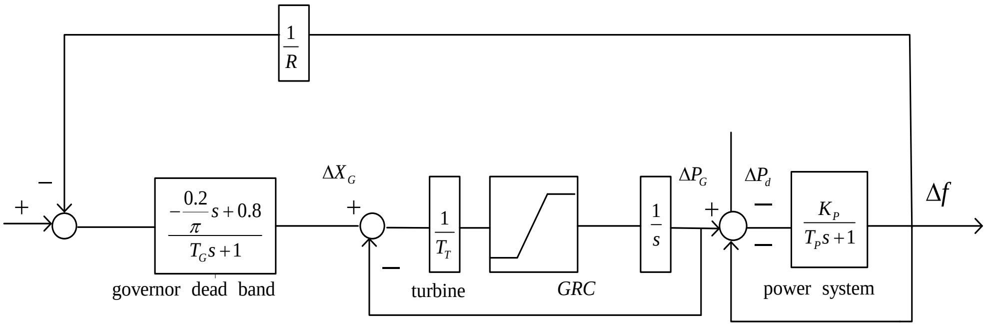

Fig. 2. Single-region power system with governor dead band and GRC

3. Linear ADRC control

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:

$$y^{(r)}(t) = bu(t) + f\left(y(t), u(t), d(t)\right) \tag{3}$$

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

$$z_1 = y, z_2 = \dot{y}, \ldots, z_r = y^{(r-1)}, z_{r+1} = f\left(y,u,d\right) \tag{4}$$

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

$$\begin{cases} \dot{z} = Az + Bu + Eh \\ y = Cz \end{cases} \tag{5}$$

Where

$$A=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\\vdots&\vdots&\vdots&\ddots&\vdots\\0&0&0&\cdots&1\\0&0&0&\cdots&0\end{bmatrix}_{(r+1)\times(r+1)},B=\begin{bmatrix}0\\0\\\vdots\\b\\0\end{bmatrix}_{(r+1)\times 1},E=\begin{bmatrix}0\\0\\\vdots\\0\\1\end{bmatrix}_{(r+1)\times 1}$$

$$C=\begin{bmatrix}1&0&0&\cdots&0\end{bmatrix}_{1\times(r+1)},z=\begin{bmatrix}z_1&z_2&\cdots&z_r&z_{r+1}\end{bmatrix}^T$$

According to the principles of modern control theory, linear extended state observer (LESO) is defined as:

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

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:

$$L=\begin{bmatrix}\beta_1&\beta_2&\cdots&\beta_r&\beta_{r+1}\end{bmatrix}^{\mathrm{T}} \tag{7}$$

When $A-LC$ asymptotically stabilizes, $\hat{z}_1(t),\cdots,\hat{z}_r(t)$ and z_{r+1} approach to $y(t),\cdots,y^{(r)}(t)$ 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:

$$u(t)=\frac{-\hat{z}_{r+1}(t)+u_0(t)}{b} \tag{8}$$

Then, the controlled system (3) becomes

$$y^{(r)}(t)=f(y,u,d)-\hat{z}_{r+1}(t)+u_0(t) \tag{9}$$

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:

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

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

$$u_0(t)=-k_1y(t)-k_2\dot{y}(t)-\cdots-k_ry^{(r-1)}(t) \tag{11}$$

Since $\hat{z}_1(t),\cdots,\hat{z}_r(t)$ approaches $y(t),\cdots,y^{(r)}(t)$, the final control law is approximated as

$$u(t)=\frac{k_1\hat{z}_1(t)+\cdots+k_r\hat{z}_r(t)+\hat{z}_{r+1}(t)}{b}=-K\hat{z} \tag{12}$$

Where

$$K=\begin{bmatrix}k_1 & k_2 & \cdots & k_r & 1\end{bmatrix}/b \tag{13}$$

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

$$\left|sI-(A-LC)\right|=s^{r+1}+\beta_1 s^r+\cdots+\beta_{r+1} \tag{14}$$

For simplicity, assume that all observer poles are configured at $-w_o$, then:

$$s^{r+1}+\beta_1 s^r+\cdots+\beta_{r+1}=(s+w_o)^{r+1} \tag{15}$$

Therefore

$$\beta_i=\binom{r+1}{i}w_o^{\,i},\ i=1,\cdots,r+1 \tag{16}$$

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 β_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 $\hat{z}_1(t),\cdots,\hat{z}_r(t)$ approximate $y(t),\cdots,y^{(r)}(t)$, the state feedback closed-loop characteristic equation is:

$$\left|sI-(A-BK)\right|=s\left(s^r+k_n s^{r-1}+\cdots+k_2 s+k_1\right) \tag{17}$$

Similarly, for simplicity, all controller poles (except the origin) can be configured at $-w_c$:

$$s^r + k_r s^{r-1} + \cdots + k_2 s + k_1 = (s + w_c)^r \tag{18}$$

Hence

$$k_i = \binom{r}{i-1} w_c^{\,n-i+1}, i = 1, \cdots, r \tag{19}$$

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

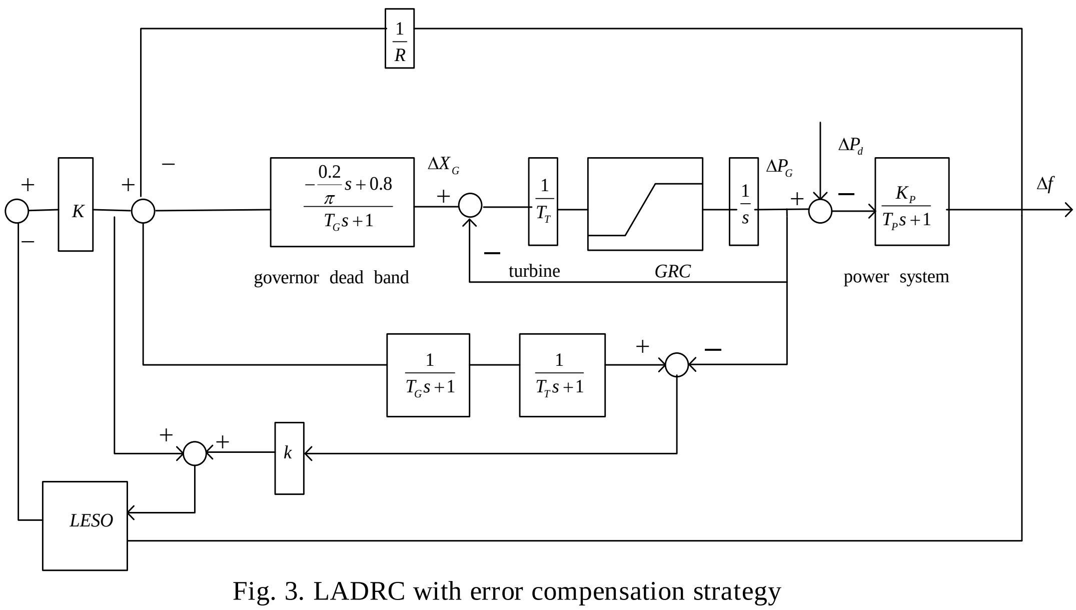

Fig. 3. LADRC with error compensation strategy

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]:

$$\begin{aligned}&K_P = 120, T_P = 20, T_T = 0.3,\\ &T_G = 0.08, R = 2.4\end{aligned} \tag{20}$$

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 $\Delta P_d = 0.01(t = 1s)$ 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.

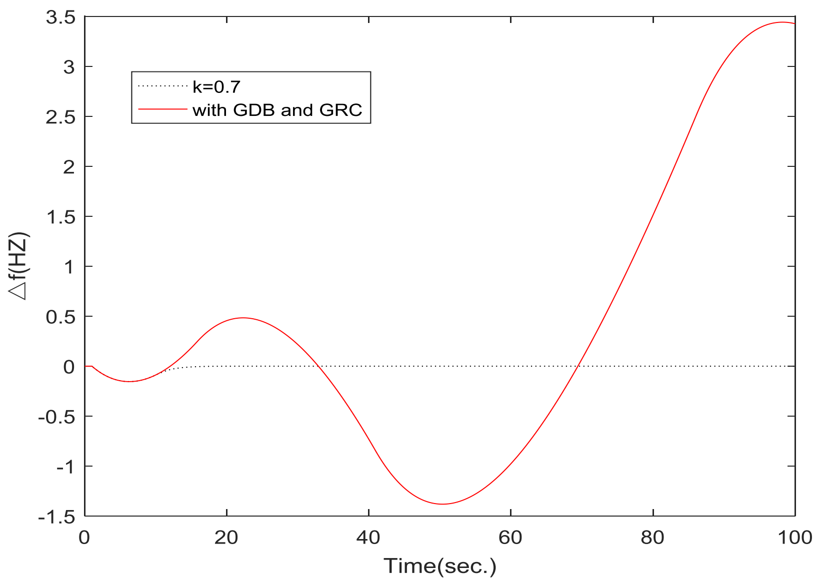

Fig. 4. LADRC power system step response using error compensation strategy ($k = 0.7$)

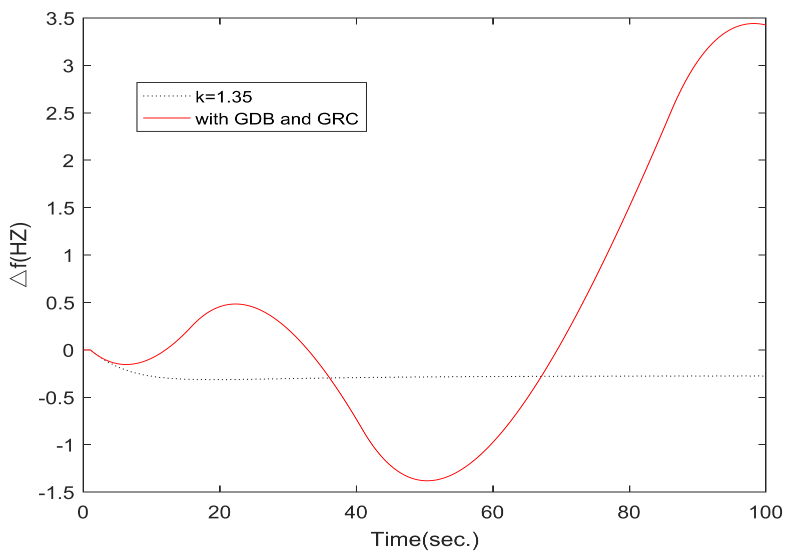

Fig. 5. LADRC power system step response using error compensation strategy ($k = 1.35$)

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.

Acknowledgments

This research was supported by grants from Henan Institute of Technology High-level Talent Research Startup Fund (KQ1854), Xinxiang Scientific and Technological Research Project (CXGG17011), Henan Province 2017 Young Backbone Teacher Training Program for Colleges and Universities (2017GGJS170).

R E F E R E N C E S

[1] W. Tan, "Load frequency control: problems and solutions", Proceedings of the 30th Chinese Control Conference, Yantai, China, July 22-24, 2011, pp. 6281-6286.

[2] H. Saadat, "Power system analysis", McGraw-Hill, 1999.

[3] A. Khodabakhshian, M Edrisj, "A new robust PID load frequency controller", Control Engineering Practice, **vol. 16**, no. 9, 2008, pp. 1069-1080.

[4] E. S. Ali, S. M. Abd-Elazim, "Bacteria foraging optimization algorithm based load frequency controller for interconnected power system", Electrical Power Energy System, **vol. 33**, no. 3, 2011, pp. 633-638.

[5] W. Tan, "Unified tuning of PID load frequency controller for power systems via IMC", IEEE Transactions on Power Systems, **vol. 25**, no. 1, 2010, pp. 341-350.

[6] K.R. SUDHA, Y B RAJU, A C SEKHAR. "Fuzzy C-means clustering for robust decentralized load frequency control of interconnected power system with Generation Rate Constraint", Electrical Power Energy Systems, **vol. 37**, no. 1, 2012, pp. 58-66.

[7] J. Sheng, J. Q. Sun, "Sliding control accounting for hardware limitation of mechanical actuators with dead band", Journal of Sound Vibration, **vol. 266**, no. 4, 2003, pp. 905-911.

[8] T. C. Chen, C. H. Yu. "Motion control with dead band estimation and compensation using GRNN for TWUSM drive system", Expert Systems with Applications, **vol. 36**, no. 8, 2009, pp. 10931-10941.

[9] M. Shioei, M. R. Toulabi, A. M. Ranjbar, "Robust multivariable predictive based load frequency control considering generation rate constraint", Electrical Power Energy Systems, **vol. 46**, no. 2, 2013, pp. 405-413.

[10] R. K. Sahu, S. Panda, S. Padhan, "A novel hybrid gravitational search and pattern search algorithm for load frequency control of nonlinear power system", Applied Soft Computing, **vol. 29**, no. 1, 2015, pp. 310-327.

[11] S. Pothiya, I. Ngamroo, "Optimal fuzzy logic-based PID controller for load frequency control including superconducting magnetic energy storage units", Energy Convers Manage, **vol. 49**, no. 10, 2008, pp. 2833-2838.
[12] K.R. Sudha, R. Vijaya Santhi, "Robust decentralized load frequency control of interconnected power system with Generation Rate Constraint using Type-2 fuzzy approach. International", Journal of Electrical Power & Energy Systems, **vol. 33**, no. 3, 2011 , pp. 699-707.
[13] T. S. Tsay, "Load–frequency control of interconnected power system with governor backlash nonlinearities", Electrical Power Energy Systems, **vol. 33**, no. 9, 2011, pp. 1542-1549.
[14] Z. Gao, "Active disturbance rejection control: A paradigm shift in feedback control system design", Proceedings of American Control Conference, Minneapolis, MN, June 2006, pp. 2399-2405.
[15] J. Q. Han, "Automatic disturbance rejection controller and its application", Control and Decision, **vol. 13**, no. 1, 1998, pp. 19-23.
[16] W. Tan, "Decentralized load frequency controller analysis and tuning for multi-area power systems", Energy Conversion & Management, **vol. 52**, no. 5, 2011, pp. 2015-2023.