International Journal of Control and Automation
Vol. 9, No. 11 (2016), pp.103-112
http//dx.doi.org/10.14257/ijca.2016.9.11.09

Research of Coordinated Control for Thermal Power Unit Based on Fractional Order Controller

Xinli Chi[1], Yuyan Zhang[1], Sheng Lin[1, 2], Qingzhong Gao[1, 2], Hongtao Yu[1] and Mingkai Yu[3]

[1.] *College of Automation Shenyang Institute of Engineering, China*
[2.] *College of Information Science and Engineering Northeastern University, China*
[3.] *Jinzhou Power Supply Branch, State Grid Liaoning Electric Power Supply Co. Ltd, Jinzhou, China*
chixinli@163.com

Abstract

Because there are two more adjustable parameters λ and μ , the fractional order $PI^{\lambda}D^{\mu}$ controller is more flexible and effective on controlling the controlled objects than the conventional PID one. A new strategy of multi-loop fractional order controller, of which the parameters are set by the Particle Swarm Optimization, is presented based on the non-linear, parameters-time-varying, and large time-delay characteristics of the thermal power unit, which is multi-variable with strong coupling.

Keywords: *Fractional order controller, thermal power unit, coordinated control*

1. Introduction

The coordinated control system of the thermal power unit is multi-variable and strongly coupling with the characteristics of non-linear, time-varying and larger time-delay. The conventional control system meets the coordinate control demands for the thermal power unit of the power grid. To develop a new suitable coordinate control policy is of crucial importance for the safe and economical operation of the thermal power unit.

The fractional order $PI^{\lambda}D^{\mu}$ controller, in which λ and μ are arbitrary constants, is firstly proposed by professor I.Podlubny. In contrast with the conventional PID controller, there are two more adjustable parameters λ and μ, which are introduced into the fractional order $PI^{\lambda}D^{\mu}$ controller as the orders of differential and integral respectively. Thus the setting range of parameters is extended, the controlled objects can be operated more flexibly, and more effective control results are expected to be arrived at 0-0.

Some researchers have applied fractional order controller to the design of multivariable nonlinear control system. For the nonlinear MIMO boiler-turbine system, on account of the characteristics of constraints and uncertainty of inputs, a kind of fractional order controller is proposed and of which the parameters are adjusted with the Particle Swarm Algorithm. The results show that better control effects can be achieved even in the condition where there is wide range of load changes and uncertainty of parameters and structure. This kind of new controller exhibits good adaptability and robustness and has more advantages than the conventional one 0-0. Some researchers have introduced the integral order switching surface of conventional sliding mode controller into the fractional order controller design and designed the global sliding mode to insure of the robustness during the whole control domain. Immediately the self-tuning of switching gain is implemented by using the fuzzy reasoning algorithm 0-0.

ISSN: 2005-4297 IJCA

Besides many other researchers have made further study of the relevant problems of fractional order controller and better control effects have been made 00.

From the above, the factional order controller has the unique advantage of large range of parameters adjustment. With this characteristic, the nonlinear property and the uncertainty of the parameters and construction of the boiler-turbine coordinated control system of the thermal power units can be overcome. The effect on the system cause the restriction of amplitude and speed of the actuator can be weaken. And then the capability of peak regulation and frequency adjustment of the power units can be improved significantly and the coordinated control level can be optimized.

2. The Fractional Order $PI^{\lambda}D^{\mu}$ Controller

2.1. The Definition for Fractional Order Controller

The basic operator of fractional order controller is ${}_aD_t^{\alpha} f(t)$, where t and a are the top and bottom limitations respectively, and α is the order of differential. The Grunwald-Letnikov definition of fractional order differential is the most widely used one in the field of fractional order differential control. The α order fractional calculus of a continuous derivative function f is

$$ {}_aD_t^{\alpha} f(t) = \lim_{h\to 0} \frac{1}{\Gamma(\alpha)h^{\alpha}} \sum_{k=0}^{[(t-a)/h]} \frac{\Gamma(\alpha+k)}{\Gamma(k+1)} f(t-kh) \tag{1} $$

where $\Gamma(\cdot)$ is the gamma function. This definition unifies the fractional differential and integral. It means that this is the fractional order differential in the case $\alpha > 0$ or the fractional order integral in the case $\alpha < 0$. [(t−a)/h] denotes the rounding operation, h denotes the step size, t and a denote the top and bottom limitations of the integral respectively. By using the Laplace transform, we get the fractional order $PI^{\lambda}D^{\mu}$ controller as follows

$$ G_c(s) = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu}, (\lambda, \mu > 0) \tag{2} $$

Where K_P is the proportional gain, K_D is the differential gain, λ is the integration order, and μ is the differential order.

As shown in the construction of $PI^{\lambda}D^{\mu}$ fractional order controller, with λ ,the integral order on the horizontal, and μ, the differential order on the vertical. The conventional integer order PI, PD and PID controller are only to be equivalent to several special points in a plane. The fractional order controller has a more flexible control construction than integer order ones.

The implementation procedure of the fractional order controller is described as follows:

The controlling term s^{α} of fractional order can be approximately calculated in the concerned frequency band $[\omega_b, \omega_h]$.

$$ s^{\alpha} \approx K \prod_{k=-N}^{N} \frac{T_k' s + 1}{T_k s + 1} $$

where N is the approximation order.

$$ K = \left(\frac{\omega_h}{\omega_b} \right)^{\frac{\alpha}{2}} $$

$$T_k' = \frac{1}{\omega_b}\left(\frac{\omega_b}{\omega_h}\right)^{\frac{k+N+\frac{1}{2}(1-\alpha)}{2N+1}}$$

$$T_k = \frac{1}{\omega_b}\left(\frac{\omega_b}{\omega_h}\right)^{\frac{k+N+\frac{1}{2}(1+\alpha)}{2N+1}}$$

The differential equation for fractional order controller is as follows:

$$G_c(t) = k_p + k_i D^{-\lambda} e(t) + k_d D^{\mu} e(t), (\lambda, \mu > 0) \tag{3}$$

2.2. Design of the Fractional Order Controller

The fractional order system is infinite-dimensional. The fractional order controller should be approximated by using the finite differential equations. In this paper, the definition of Grunwald-Letnikov is used to discretize the fractional order $PI^{\lambda}D^{\mu}$ controller. First, calculate the input error sequence e_m. Secondly, calculate the output sequence u_m of the controller by using the discrete equations. Finally, the fractional order controller will be digitized.

The concrete steps are as follows:

(1) Calculate the input sequence e_m

First calculate the error $e(t)$ between the ideal given value $r(t)$ and the output $y(t)$, that is:

$$e(t) = r(t) - y(t) \tag{4}$$

Convert (4)to discrete sequence of the discrete time series t_m:

$$e_m = r_m - y_m \tag{5}$$

(2) calculate the outputs of the controller

By using the Grunwald-Letnikov definition of fractional order calculus, convert (3)to discrete equations of the discrete time t_m (m=l,2,3,…):

$$u_m = k_p e_m + k_i h^{\lambda} \sum_{j=0}^{m} w_j^{(-\lambda)} e_{m-j} + k_d h^{-\mu} \sum_{j=0}^{m} w_j^{(\mu)} e_{m-j} \tag{6}$$

$$w_0^{(\lambda)} = 1, w_j^{(\lambda)} = (1 - \frac{\lambda+1}{j}) w_{j-1}^{(\lambda)} \tag{7}$$

Then put e_m and w_j^{λ} into(6), we can get the output value of the fractional order controller.

2.3. Parameter Identification of the Fractional Order Controller

For the fractional order system, the operator number, the order and the operator coefficients are all needed to be identified. This will increase the difficulties of the system identification of the fractional order model 0-0.

The least square method and the maximum likelihood method are the two traditional ones applied to the system identification. The gradient information is needed when using the two methods. If the identification model is not differentiable or can not to be linearized, the application of the two methods will be limited. The Particle Swarm Optimization (PSO) algorithm based on swarm intelligence theory provides an effective way to solve the similar problems. When using the Particle

Swarm Optimization algorithm, no other information is needed except for the fitness function, and this simplifies the system identification procedure.

For the Particle Swarm Optimization algorithm, every solution is regarded as a particle which has a fitness value. Similar to the other evolutionary algorithms, the solution space is initialized as a group of random data, and the optimal solution is obtained through the generation updated.

Provided that there are m particles in a three-dimensional searching space, and the particle $i(i=l,2,...,m)$ is located at $X_i=(x_{i1},x_{i2},\cdots,x_{iN})$ in space. Put Xi into the objective function, we can calculate the fitness value of particle $i(i=l,2,...,m)$. The Xi can be measured according to the fitness value. The optimal position for particle i is donated as $P_i=(p_{i1},p_{i2},\cdots,p_{iN})$, and the corresponding fitness value is known as particle best value P_{best}. As for the minimization problem, the smaller the objective function value is, the more the corresponding fitness value is.

Supposed that the objective function is denoted as $f\left(x\right)$, the best position coordinates for particle i can be calculated by using the following formulas

$$P_i(t+1)=\begin{cases} P_i(t) & f(X_i(t+1)\geq f(P_i(t)) \\ X_i(t+1) & f(X_i(t+1)\leq f(P_i(t)) \end{cases} \tag{8}$$

in which t denotes the $t-th$ generation.

The best position for the particles is denoted as $Pg=(pg1,pg2,...,pgN)$, and the corresponding fitness value is called the globally optimal solution denoted as g_{best},, then

$$P_g(t)\in\{P_0(t),P_1(t),...,P_m(t)\}\Big|\, f(P_g(t))=\min\{f(P_0(t),f(P_1(t),...,f(P_m(t)))\tag{9}$$

The searching velocity of particle i is denoted as $V_i=(v_{i1},v_{i2},\cdots,v_{iN})$, and the velocity and position of the particle can be obtained according to the following equations

$$\begin{aligned} v_{in}(t+1)&=\omega v_{in}(t)+c_1r_1(p_{in}-x_{in})+c_2r_2(p_{gn}-x_{in}) \\ x_{in}(t+1)&=x_{in}(t)+v_{in}(t+1) \end{aligned}\tag{10}$$

in which i=l,2,$\cdots m$,n=l,2,$\cdots$,N, ω is the inertia factor, c_1 and c_2 are both learning factors of which c_1 is used to adjust the step length when the particle approaches its best position and c_2 is used to adjust the step length when the particle approaches the best global position. r_1 and r_2 are two independent numbers in the interval $[0,1)$, $x_{in}\in[x_{minn}, x_{maxn}]$ determines the value range of the particle according to the actual conditions, $v_{in}\in[-v_{maxn}, v_{maxn}]$, the maximum value of one forward step v_{maxn} is determined based on the length of the taking value interval.

The flow chart of Particle Swarm Algorithm is shown in Figure 1.

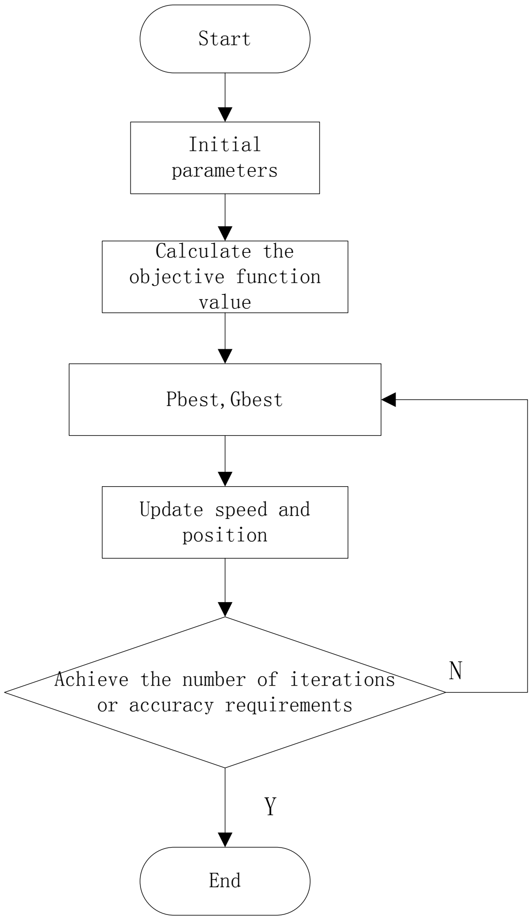


Figure 1. Flow Chart of PSO Algorithm

3. Turbine-Boiler Coordinated Control System based on Fractional Order Controller

3.1. System Description

The coordinated control system is designed based on the boiler turbine dynamic models, one of which modeled by Astrom and described as third-order non-linear differential equations is adopted in this paper, of thermal power plant. The equations are given as follows00:

$$\dot{p}_b = -0.0018u_1 p_b^{9/8} + 0.9u_b - 0.15u_w \tag{11}$$

$$\dot{P} = (0.073u_t - 0.016)p_b^{9/8} - 0.1P \tag{12}$$

$$\dot{\rho}_f = [141u_w - (1.1u_t - 0.197)p_b]/85 \tag{13}$$

$$L = 0.05(0.13073\rho_f + 100\alpha_{cs} + q_e/9 - 67.975) \tag{14}$$

$$\alpha_{cs} = \frac{(1-0.001538\rho_f)(0.8p_b - 25.6)}{\rho_f(1.0394 - 0.0012304p_b)} \tag{15}$$

$$q_e = (0.854u_t - 0.147)p_b + 45.59u_b - 2.54u_w - 2.096 \tag{16}$$

where p_b is drum pressure, kg/cm^2. P is the unit load, MW. ρ_f is the liquid density in drum, kg/cm^2. u_t, u_b, u_w are the main steam value, the fuel governing valve and the water supply valve respectively. L is the drum water level, m. α_{cs} is the factor of merit of steam. q_e is the mass flux of steam, kg/s.

Limited by the amplitude and the rate, the input signals are given as follows0:

$$\begin{cases} 0 \le u_b \le 1, & |du_b/dt| \le 0.007/s \\ 0 \le u_t \le 1, & -2/s \le du_b/dt \le 0.02/s \\ 0 \le u_w \le 1, & |du_b/dt| \le 0.05/s \end{cases} \tag{17}$$

It is showed that this is a typical 3-input and 3-output non-linear system with strong variable coupling. The system must be controlled in order that the output power can respond as fast as the load of power grid changes, the drum pressure fluctuations can be limited in the allowance range, and the water level can be kept constant.

3.2. Design Method

The boiler turbine coordinated control system is shown in the inset of Figure 2.

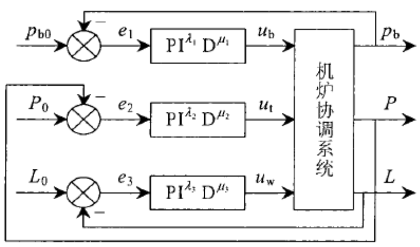


Figure 2. Structure Diagram for Boiler Turbine Coordinated Control System

As shown in Figure 2, the fractional order controllers $PI^{\lambda 1}D^{\mu 1}$, $PI^{\lambda 2}D^{\mu 2}$ and $PI^{\lambda 3}D^{\mu 3}$ control the drum pressure p_b, the power P and the drum water level L by manipulating u_t, u_b and u_w, respectively. p_{b0}, P_0 and L_0 are the corresponding set values, respectively. The main role of the boiler-turbine coordinated control system is to insure that the output power of the units can respond to the change in load of the power grid. The thermal inertia of the boiler is very great and the fuel regulation has a great lag. The adjustment of the main steam valve could change the input air quickly and the power in the meanwhile. To insure the rapidness of the power response, the power is manipulated with the main steam valve and the drum pressure is manipulated with the fuel valve. The drum water level is decided by the water supply valve, relatively independent.

3.3. Engineering Application

This control strategy is applied to the coal-fired units(2×330WM) of Yingkou thermal power plant of Yingkou power and heat Co. Ltd of China Huaneng. In order to obtain the assured following response characteristic and robust stability, the particle swarm optimization is used.

As shown in Table 1 there are three balance working points for the system.

Table 1. Balance Point of Working Condition

系统参数	工况点		
	1	2	3
p_b/(kg/cm^2)	86.40	108.00	129.60
P/MW	36.65	66.65	105.80
ρ_f/(kg/cm^3)	342.4	427.2	513.6
u_b	0.209 0	0.340 0	0.504 6
u_t	0.552 0	0.690 0	0.828 0
u_w	0.255 6	0.436 0	0.662 5

During the process of optimization the system firstly works at the point of No. 2. Then the drum pressure and the output power change gradually from the point of No. 2 to the one of No. 3. And the drum water level is kept constant during this process. The objective function is the weighted sum of integral of square error of all the control loops.

$$J = w_1\int_0^\infty e_1^{\,2}dt + w_2\int_0^\infty e_2^{\,2}dt + w_3\int_0^\infty e_3^{\,2}dt \tag{18}$$

where $e_1 = p_{bo} - p_b$, $e_2 = P_0 - P$,and $e_3 = L_0 - L$. w_1 , w_2 and w_3 are the weighted coefficients of the control loops, respectively. The relative importance of every output can be redistributed by using this method. The same weighted coefficient is set for all the control loops to make sure that they have the same importance. If it is necessary to make one of the control loops more important than the others, we should reselect the weighting coefficients of the loop to make sure that the parameter adjustment of this loop can be carried out well and fast.

The standard particle swarm optimization is used during the optimization process. The relevant parameters are assigned as follows: the population size is 30, the maximum number of iterations is 150. The optimization results are showed below:

$$k_{p1} = 0.0091, k_{i1} = 0.0027, k_{d1} = 0.0046, \lambda_1 = 0.5114, \mu_1 = 0.0113;$$

$$k_{p2} = 0.0103, k_{i2} = 0.0035, k_{d2} = 0.0004, \lambda_2 = 0.4946, \mu_2 = 0.4574;$$

$$k_{p3} = 23.3322, k_{i3} = 0.0198, k_{d3} = 0.0005, \lambda_3 = 0.0623, \mu_3 = 0.0002。$$

The effects for engineering application are shown in Figure 3 and 108. Figure 3 shows the random selected primary frequency modulation capability curve on August 21 of 2015 of No.1 unit of Yingkou thermal power plant of Yingkou power and heat Co. Ltd of China Huaneng, and Figure 4 shows the tracking capability curve of No.1 unit in the same period. This shows that satisfactory results can be obtained by using the. fractional order $PI^{\lambda}D^{\mu}$ controller, which exhibits perfect adaptability and robustness.

4. Conclusion

Conventional control strategy cannot meet the requirements of the power grid to the coordinated control of the unit plant because of the characteristics of nonlinearity, time-varying parameters and longtime delay accompanied with multi-variables and strong coupling. In this paper, on the base of the analysis of the characteristics of fractional order controller, a new implementation of fractional order controller suitable for DCS is proposed by marvelous treatment.

With the new control method, the practical results show that the capability of participating the frequency and peak load modulation of power grid is enhanced, the regulatory quality of the primary parameters of the unit plant is improved, the stability and economy of unit operation are both improved, and technical advantage is supplied for market competition and bidding for accessing to networks.

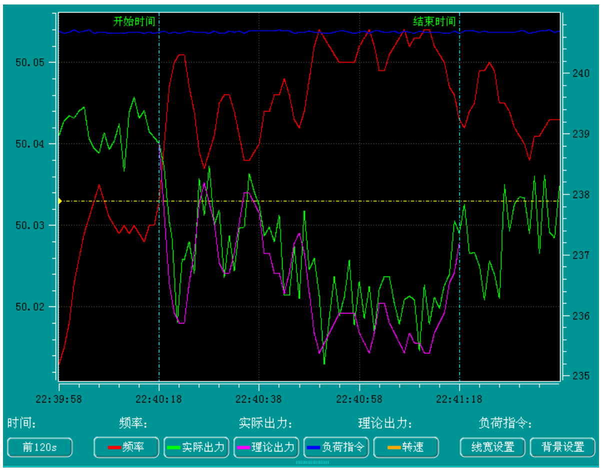


Figure 3. Primary Frequency Modulation Capability Curve of No.1 Unit of Yingkou Thermal Power Plant of Yingkou Power and Heat Co. Ltd of China Huaneng

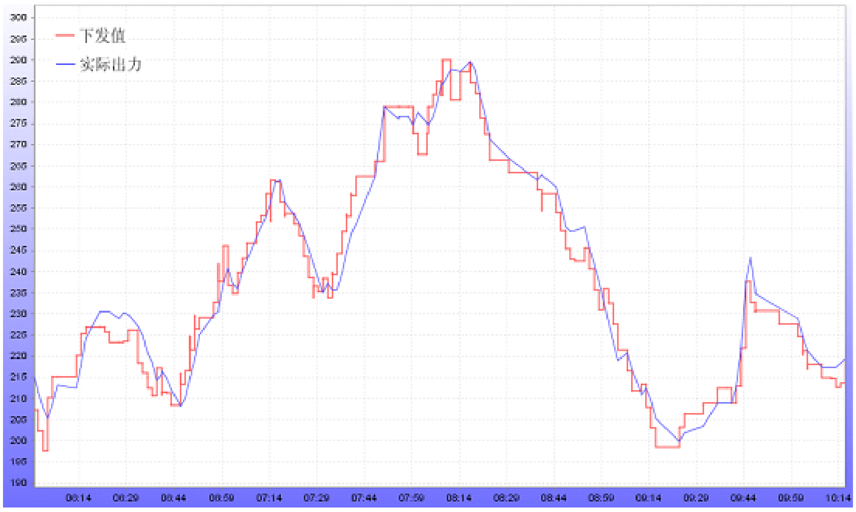


Figure 4. Tracking Capability Curve of No.1 Unit of Yingkou Thermal Power Plant of Yingkou Power and Heat Co. Ltd of China Huaneng

Acknowledgement

This work was supported in part by the National Natural Science Foundation of China under Grant 61372195, 61304069 and 61371200, Science & Technology Research of Liaoning Provincial under Grant No. L2014530, L2015366 and L2015367.

References

[1] I. Podlubny, "Fractional-order systems and PI/sup/spl lambda//D/sup/spl mu//-controllers", Automatic Control, IEEE Transactions on, vol. 44, no. 208, **(1999)**.

[2] I. Podlubny, I. Petraš and B. M. Vinagre, "Analogue realizations of fractional-order controllers", Nonlinear dynamics, vol. 29, no. 281, **(2002)**.

[3] P. Daogang, Y. Ping and W. Zhiping, "Fuzzy Immune PID Control and Its Application to Main Steam Temperature Control System", Computer Automated Measurement & Control, vol. 3, **(2005)**.

[4] H. P. Corporation, "A Study of Nonlinear Fractional Differential Equations of Arbitrary Order with Riemann-Liouville Type Multistrip Boundary Conditions", Mathematical Problems in Engineering, vol. 93, no. 343, **(2013)**.

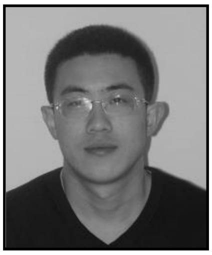
[5] L. Wang，J.J. Li，Y.H. Wang and Q.X. Guan, "Research on Coordinated Control System for Boiler-Turbine Units Based on Fractional-Order Control", Advanced Materials Research, vol. 276, no. 732, **(2013)**.
[6] Bohannan and W. Gary, "Analog fractional order controller in temperature and motor control applications", J. Vib. Control, vol. 14, no.1487, **(2008)**.
[7] J. Wang, Y. Zhou and M. Fečkan, "Abstract Cauchy problem for fractional differential equations", Nonlinear Dynamics, vol. 71, no. 685, **(2013)**.
[8] C. Ma and Y. Hori, "Fractional-Order Control: Theory and Applications in Motion Control", IEEE Industrial Electronics Magazine, vol. 4, no. 6, **(2007)**.
[9] D. Corinaldi，M. Palpacelli，L. Carbonari，L. Bruzzone and G. Palmieri, "Experimental analysis of a fractional-order control applied to a second order linear system",Mechatronic and Embedded Systems and Applications (MESA), vol. 1, **(2014)**.
[10] M. M. Khader, T. S. E. Danaf and A. S. Hendy, "A computational matrix method for solving systems of high order fractional differential equations", Applied Mathematical Modelling, vol. 37, no. 4035,**(2013)**.
[11] R. Melício，V.M.F. Mendes and J.P.S. Catalão, "Fractional-order control and simulation of wind energy systems with PMSG/full-power converter topology", Energy Conversion & Management, vol. 51, no. 1250, **(2010)**.
[12] L.I. Zhi-Min，Q.Z. Sun，Y. Sun and X.P. Han, "Design of Fractional-order Controller for Diesel Engine System Based on BF-PSO", Control Engineering of China, vol. 19, no. 3, **(2012)**.
[13] H. Ramezanian，S. Balochian and A. Zare, "Design of Optimal Fractional-Order PID Controllers Using Particle Swarm Optimization Algorithm for Automatic Voltage Regulator (AVR) System", Journal of Control Automation & Electrical Sysem, vol. 5, no. 601, **(2013)**.
[14] J. Lei，X. Meng and Z. Liu, "Freestyle Fractional Order Controller Design with PSO for Weapon System", Energy Procedia, vol. 13, no.7577, **(2011)**.
[15] K. J. Astrom and R. D. Bell, "Drum-boiler dynamies", Automatica, vol. 36, no. 363, **(2000)**.
[16] M.S. Tavazoei, "Notes on integral performance indices in fractional-order control systems", Journal of Process Control, vol. 3, no. 20, **(2010)**.

Authors

Xinli Chi, he received the M.S. degree from Liaoning University, Shenyang, China, in 2004. He is now an associate professor with Shenyang Institute of Engineering. His research interests include complex industry control, intelligence algorithm, and power system dynamic simulation.

Yuyan Zhang, she received the B.S. degree, M.S. degree, and Ph. D. degree from Northeastern University, Shenyang, China, in 1999, 2002, and 2014, respectively. She is now an associate professor with the Automation Department of Shenyang Institute of Engineering. Her research interests include fuzzy control and fuzzy systems, chaotic control, and complex systems.

Sheng Lin, he received the M.S. degree from Northeastern University, Shenyang, China, in 2007. He is now a lecturer with Shenyang Institute of Engineering. His research interests include complex process control, wireless power transfer and power quality monitoring.



Qingzhong Gao, he received the M.S degree from Northeastern University in 2009. Now he is a doctoral candidate in Northeastern University. He is now a lecturer with Shenyang Institute of Engineering. His main research interest is key technologies of adjustable permanent magnetic coupler. His research interests include Speed Permanent magnet technologies.

Hongtao Yu, he received the B.S. degree, M.S. degree, and Ph.D. degree from Northeastern University, Shenyang, China, in 2001, 2007, and 2014, respectively. Since 2007, he has been with Shenyang Institute of Engineering. His research interests inlude intelligent control, mathematical modeling and optimization.

Mingkai Yu, he received the B.S. degree of Engineering from Northeast Dianli University in 1993 and the M.S degree of Engineering from EPRI of China in 2006. At present he works in Jinzhou Power Supply Branch, State Grid Liaoning Electric Power Supply Co. Ltd as the vice-chief engineer.

Recently, his research area includes distributed generation, cooperation control, etc.