Applying fractional order system to design coordinated control system in primary frequency and automatic generation control for large coal-fired units

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Abstract. The large coal-fired units should have the ability of primary frequency (PF) and automatic generation control (AGC) to meet the requirements of grid security. In this paper, coordinated control system (CCS) with fractional order control (FOC) is designed in PF and AGC for large coal-fired units. An implementation of fractional order PID (FOPID) controller in distributed control system (DCS) is proposed. The engineering application results show that the algorithm is easy to implement in engineering, which can overcome the large delay and inertia of the fuel system, and effectively improve the performance of PF and AGC.

1. Introduction
With the increasing proportion of new energy in the power grid structure, the participation of large coal-fired units in frequency adjustment and peak regulation is of great significance for the safe operation of the grid side. In view of power quality, two regulations for power grids of China with PF and automatic generation control (AGC) performance requirements are proposed[1]. The load response is limited because the difficulty in applying AGC to a project is the large delay and inertia of the large capacity unit. In order to overcome the influence of fuel-turbine characteristics change under wide load change and make the unit meet the grid side PF and load requirements, this paper studies the coordinated control system (CCS) of coal-fired units based on fractional order control (FOC).

Fractional order PID (FOPID) control is the promotion and development of basic PID control[2-4]. Introducing the integration order and the difference order can make the controller more flexible and powerful. The FOPID controller is insensitive to changes in the parameters of the controlled object and is more robust and suitable for nonlinear systems.

This paper studies the mechanism of FOC and proposes the implementation method of FOC. The algorithm has been implemented in engineering applications and verified by actual procedures. For various power load demand changes and fuel-turbine CCS parameters and structural uncertainties, FOC controllers have better robustness and adaptability than basic PID controllers.

The engineering application results show that the algorithm uses general algorithm blocks in various distributed control systems (DCS), which is easy to implement in the project. In addition, the algorithm can overcome the large delay and inertia of the fuel system and effectively improve the PF and AGC performance of the fuel-turbine CCS.
2. FOC System

2.1. Fractional Calculus

By introducing the concept of fractional operator, it can unify the differentiator and integrator \( _{l}D_{u}^{x}f(t) \), where \( l \) is the lower limit, \( u \) is the upper limit, and \( x \) is the order. Riemann-Liouville definition is one definition of the fractional differentiation

\[
_{l}D_{u}^{x}f(t) = \frac{1}{T(p-x)} \left( \frac{d}{dt} \right)^{p} \int_{l}^{u} \frac{f(\tau)}{(t-\tau)^{1+(p-x)}} d\tau ,
\]

(1)

Where \( T(\cdot) \) is the well-known Euler's gamma function, for \( p - 1 < x < p \). Grünwald-Letnikov definition based on the concept of fractional differentiation is another definition given by

\[
_{l}D_{u}^{x}f(t) = \lim_{c \to 0} \frac{1}{T(x)h^{c}} \sum_{i=0}^{(u-x)/c} T(\alpha + i)(l+i) f(l-ic) .
\]

(2)

2.2. Laplace Transform of Fractional Order System

It can be given by a transfer function form for a fractional order differential equation, provided both the signals \( u(t) \) and \( y(t) \) are relaxed at \( t = 0 \)

\[
G(s) = \frac{a_{1}s^\alpha + a_{2}s^{\beta} + \cdots + a_{p}s^{\gamma}}{b_{1}s^\alpha + b_{2}s^{\beta} + \cdots + b_{p}s^{\gamma}} ,
\]

where \( (a_{p}, b_{p}) \in R^{2}, (x_{p}, y_{p}) \in R^{2}, \forall (p \in N) \) (3)

2.3. Characteristics of Fractional Order Controller

Involving an integrator of order \( \alpha \) and a differentiator of order \( \beta \), \( PI^{\alpha}D^{\beta} \) is the most common form of a FOPID controller[2-4], where \( \alpha \) and \( \beta \) may be any real number, whose transfer function is given by the form as

\[
G_{p}(s) = K_{p} + \frac{K}{s^{\alpha}} + K_{p}s^{\beta} , \quad (\alpha, \beta > 0)
\]

(4)

\( s^{\alpha} \) is the integrator term, which means that there is a line with the slope of \( -20 \alpha \) dB/dec on a semi-logarithmic plane. As the order of the fractional integrator increases, the slope of the amplitude-frequency characteristic gradually changes. Fractional differentiation and integration can be used to adjust the amplitude and logarithmic amplitude at the cutting frequency. Compared with the basic PID controller, only a multiple of 20dB/dec can be selected, and the fractional order controller can adjust the shape of the bauld more freely[6]. For instance, the robustness of the closed loop system may be enhanced if a flatter curve at the cutting frequency is selected. In addition, the variation of the fractional differential and the integral order can change the frequency characteristics more flexibly than the change of the integral and differential coefficient, which can enhance the robustness of the system. For some control problems, the performance of the best fractional order controller will be far superior to the best integer order PID controller.

2.4. Approximate Calculation and Implementation of Fractional Operators

Given \( N \) is the approximate order, the fractional order differentiator \( s^{i} \) can be realized in the frequency range \([\omega_{h}, \omega_{h}]\) of interest as follow
\[ s^\star \approx \prod_{i=1}^{N} T_i s + 1, \quad \text{for} \quad Q = \left( \frac{\omega_h}{\omega_h} \right)^{\frac{\alpha}{\beta}}, \quad T_i' = \frac{1}{\omega_h} \left( \frac{\omega_h}{\omega_h} \right)^{\frac{i+N+1}{2N+1}}, \quad T_i = \frac{1}{\omega_h} \left( \frac{\omega_h}{\omega_h} \right)^{\frac{1+1}{2N+1}}. \quad (5) \]

In this way, the fractional order differentiator \( s^\star \) should be simply implemented by using LEAD/LAG algorithm blocks with the number of \( 2N+1 \), when the approximate order \( N \) is given. For engineering applications, 2 or 3 can be chosen for \( N \), which can achieve sufficient accuracy and ensure that the control system is not so complicated. The implementation of FOPID controller in DCS is shown in figure 1.

In the time domain, the control signal \( u(t) \) can be expressed as

\[ u(t) = K_p e(t) + K_D T_N e(t) + K_I T_N^{-1} e(t). \quad (6) \]

If \( \alpha = \beta = 0 \), it becomes just a P controller; when \( \alpha = 1 \) and \( \beta = 0 \), it is a PI controller; when \( \alpha = 0 \) and \( \beta = 1 \), it is a PD controller; while \( \alpha = \beta = 0 \), it is a classical PID controller; all of which can be simply considered as the special cases of FOPID controller. The FOPID controller is more flexible and insensitive to changes in controlled system parameters[2-4], and provides an opportunity to better adjust the dynamics of the system as it has two additional degrees of freedom to set, which also theoretically proves its advantages over traditional methods.

3. Fuel-turbine CCS Based on FOC

The fuel-turbine CCS is the most important control part, which must take both fuel master and turbine master into account together, for fuel control is slow but turbine control is fast. After coordinated processing, CCS can accept the actual load command, output the turbine master command and the fuel master command, so that the fuel master and turbine master can work together to achieve the external demand for the unit load; the CCS can maintain the pressure at the setting value. Ensure the energy balance between the fuel and turbine control to keep the unit safe and stable.

As is shown in figure 2, CCS can be divided into three modes: turbine following (TF, \( Q_1 = 0, Q_2 \neq 0, Q_3 \neq 0, Q_4 = 0 \)), fuel following (FF, \( Q_1 \neq 0, Q_2 = 0, Q_3 = 0, Q_4 \neq 0 \)) and comprehensive CCS mode (\( Q_1 \neq 0, Q_2 \neq 0, Q_3 \neq 0, Q_4 \neq 0 \)). For the TF mode, the pressure is controlled by turbine master, and the unit load is controlled by fuel master. In this mode, the unit operates stably, but due to the slow load response, the control accuracy is poor, and the unit cannot meet the load requirements. For the BF mode, the pressure is controlled by fuel master, and the unit load is controlled by turbine master. In this mode, the load response rate is fast and the control precision is good, but the pressure fluctuation is large and the stability is poor, which can meet the load requirements of grid, but the unit operation is not safe and stable; for the comprehensive CCS mode, the pressure and unit load are controlled by the turbine master and the fuel master together. In this mode, the performance of the unit is between the TF and BF mode, which is the common control mode.
Figure 2. Fuel-turbine CCS based on FOC.

Regardless of the control method used, the basic PID controller is difficult to significantly improve the responsiveness of the PF and AGC, while ensuring safe and stable operation of the unit. Therefore, it is necessary to break through the traditional control methods and adopt advanced control technology to design a new type of CCS suitable for the characteristics of the unit. The FOPID controller can be considered as an extension of the basic PID controller. Variations in fractional differential and integral orders can more subtly alter the frequency response curve of the system, and can also indicate the intensity of fractional differentiation and integration[7], which increases the flexibility of system performance tuning. At the same time, the fractional differentiator has a memory function, which can ensure the influence of historical information on the present and future, and help to change the control quality of the system[8].

Based on the comprehensive CCS mode, this paper applies the FOPID controller to the design of fuel-turbine CCS, overcoming the large delay and inertia of fuel control and the influence of fuel-turbine on the characteristic changes under wide load changes. In this way, the coal-fired unit can meet the load requirements of the grid side and effectively improve the PF and AGC performance of the fuel-turbine CCS. The modification logic of the fuel master is shown in figure 3.

Figure 3. Modification logic of fuel master.
4. Application
In this paper, the newly designed fuel-turbine CCS based on the FOPID controller has been applied to the 300MW subcritical coal-fired unit. Through control logic optimization, debugging and test of load up and down, the best control parameters are obtained. The PF and AGC performance is better than the grid requirements, which effectively improves the main parameters of the unit. The PF and AGC performance curves of the unit are shown in figure 4 and figure 5.

Figure 4. PF control curve.

Figure 5. AGC performance curve.

5. Conclusion
The fuel-turbine CCS is a nonlinear, multivariable, strongly coupled system with time-varying parameters, large delays and inertia. Traditional control strategies cannot meet the grid requirements of CCS. This paper analyses the characteristics of FOC, and proposes the FOC implementation of DCS control system through ingenious transformation. According to the characteristics of the unit, the integrated fuel-turbine CCS based on FOPID controller is proposed, which has been proved to solve the unit control problem by engineering application successfully.

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