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# Time Delay Compensation Based Active Disturbance Rejection Control for Thermal Process

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Thermal process is typically nonlinear and uncertain. The control design becomes even more challenging in the presence of time-varying delay. Active disturbance rejection control (ADRC) has been shown to be an effective tool in dealing with real world problems of dynamic uncertainties and nonlinearities. In particular, to overcome the time-varying delay, time delay compensation based ADRC method is addressed. Contrary to Smith predictor, the most efficient feature of the proposed method is that it works without time delay models. The influence of time delay is regarded as the external disturbance, and is estimated by the designed disturbance observer. Validity of the proposed method in the cases of both constant delay and time-varying delay with unknown disturbance for the typical thermal process is verified by simulation results.

## 1. Introduction

In the last few decades, global warming and climate change are undeniably predominant among the most important issues in the world (Mwangi et al., 2015). To resolve the issue coupled with threat to energy security and air pollution, approaches of efficient energy transformation and sustainable power generation have attracted increasing attention (Wang et al., 2018). Renewable energy, such as solar (Poompavai and Kowsalya, 2019), wind (Sahu, 2018), hydro (Singh and Singal, 2017), hydrogen (Bukar and Tan, 2019), biomass (He et al., 2018) and so on, has been widely investigated from materials to system integration. In addition, ultra-supercritical (Liu et al., 2015) and double-reheat (Zhou et al., 2016) technologies are applied to the coal-fired power plants for high efficiency and low emissions .

Process control of the energy system plays an important role in exploring their potential advantage. However, various unique features make it a challenge task. Among them, time delay is pervasive in different energy systems. A robust controller was proposed for the solar plants with distributed collectors to reach the desired specifications despite variations of time delays and time constants (Cirre et al., 2010). To tackle the obvious control error caused by communication time delay in air conditioning loads control for consuming photovoltaic power and wind power, a network predictive control system was designed (Yang et al., 2017). For the biomass boiler, time delay had a crucial impact on the fuel feed, which was only able to assure long-term load requests. Consequently, in (Gölles et al., 2014) Smith predictor was used to compensate the time delay element. To overcome the challenges brought by coupling, inertia and time delay for the integration of post-combustion CO2 capture system with power plant, the centralized model predictive control was proposed for the operation (Wu et al., 2019). In order to deal with the fluctuant and stochastic renewable energy, higher requirement is imposed for the flexible operation of conventional coal-fired power plants (Brouwer et al., 2015). The time delay in the boiler-turbine unit of the coal-fired power plant mainly come from the pulverizing system and the complex layout of steam and water. The difficulty increases especially when the time delay varies according to the different operation conditions.

Active disturbance rejection control (ADRC) is a well-known technique that can deal with uncertainty of the process, including the modelling mismatch and the external unmeasured disturbance. Due to its performance and simplicity, ADRC has been applied to different areas, such as gasoline engines (Xue et al., 2015) ,flight control (Ma et al., 2017), energy storage system (Chang et al., 2015) and so on. The main principle of ADRC is the estimation and actively compensation via extended state observer (ESO). However, its performance

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declines when there exists time delay because information of input and output that enters ESO does not match in time series. Some researchers have proposed some improvements for the original ADRC. The Smith predictor based ADRC was used to predict the output without time delay and estimate the lumped disturbance (Zheng and Gao, 2014). In (Zhao and Gao, 2014), a time delay block was added manually at the entrance of ESO so that the input and output information matches in time series. However, the above methods rely on the model of time delay. When the time delay varies with dynamic character of the process, expected performance could not be achieved.

In this paper, a time delay observation and compensation based ADRC is proposed for the typical boiler-turbine unit process. This study contributes to the research on the ADRC control structure for the process with varying time delay, which can accommodate to different time delay models at different operation conditions and improve the control performance.

## 2. Time delay compensation based ADRC

### 2.1 Observation and estimation of time delay

Without loss of generality, a system with input delay and output delay can be described as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t-T_1) \\ y(t) &= Cx(t-T_2) \end{aligned} \tag{1}$$

where $x \in \mathbf{R}^{n\times 1}$ is the state vector, $u$ and $y$ are the input and output of the process. Matrix $A \in \mathbf{R}^{n\times n}$ , $B \in \mathbf{R}^{n\times 1}$ and $C \in \mathbf{R}^{1\times n}$ denote the system matrix of the process. $T_1$ and $T_2$ are the input and output time delay, respectively. The initial state of this process is assumed zero, i.e. $x(0) = o_{n\times 1}$. It was pointed out that output time delay was equivalent to input time delay in mathematics (Chen et al., 2018). Thus, the output time delay is incorporated into input time delay as following

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t-T) \\ y(t) &= Cx(t) \end{aligned} \tag{2}$$

where $T = T_1 + T_2$. System (2) can be expressed as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) - B\left[u(t) - u(t-T)\right] \\ y(t) &= Cx(t) \end{aligned} \tag{3}$$

If it is defined that

$$d_{td}(t) = u(t) - u(t-T) \tag{4}$$

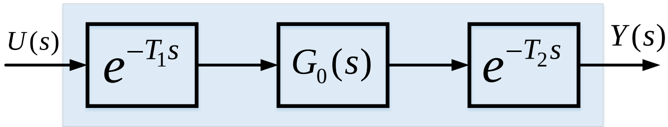
the equivalent system can be obtained

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) - Bd_{td}(t) \\ y(t) &= Cx(t) \end{aligned} \tag{5}$$

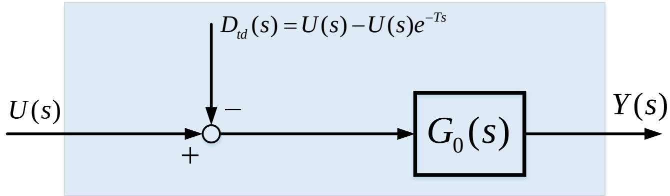
The term $d_{td}(t)$ can be regarded as the effect of time delay. In process (5), the time delay functions as the external disturbance. It is intuitional that estimation of this effect of time delay helps make a precise prediction of the process output. This kind of equivalence can be depicted in Figure 1.

The system (5) can be augmented as

$$\begin{aligned} \begin{bmatrix} \dot{x}(t) \\ \dot{d}_{td}(t) \end{bmatrix} &= \begin{bmatrix} A & -B \\ o_{1\times n} & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ d_{td}(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) \\ y(t) &= \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ d_{td}(t) \end{bmatrix} \end{aligned} \tag{6}$$




(a) System with time delay




(b) Equivalent system with effect of time delay

*Figure 1: System with time delay and its equivalency*

The corresponding observer is designed to estimate the effect of time delay as

$$\begin{bmatrix} \dot{\hat{x}}(t) \\ \dot{\hat{d}}_{td}(t) \end{bmatrix} = \begin{bmatrix} A & -B \\ o_{1\times n} & 0 \end{bmatrix} \begin{bmatrix} \hat{x}(t) \\ \hat{d}_{td}(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) + L_{td}\left(y(t) - \hat{y}(t)\right)$$
$$\hat{y}(t) = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} \hat{x}(t) \\ \hat{d}_{td}(t) \end{bmatrix} \tag{7}$$

where $L_{td}$ is the gain of the observer. Once the gain $L_{td}$ is well chosen, the estimation of the effect of time delay $\hat{d}_{td}(t)$ can be obtained.

Similar to Smith predictor, the output of the process can be compensated based on the estimation value $\hat{d}_{td}(t)$. The structure can be found in Figure 2.

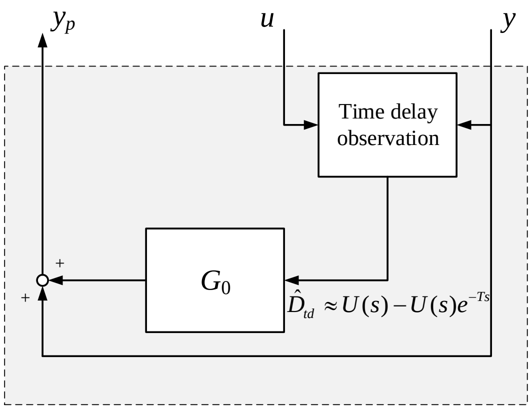



*Figure 2: Observation and compensation of time delay*

In Figure 2, $G_0(s)$ is the process dynamics without time delay, and the process is expressed as $Y(s) = G_0(s)U(s)e^{-Ts}$. When $\hat{d}_{td}(t)$ is utilized, it can be got

$$\begin{aligned} G_0(s)\hat{D}_{td}(s) &\approx G_0(s)\left(U(s) - U(s)e^{-Ts}\right) \\ &= G_0(s)U(s) - G_0(s)U(s)e^{-Ts} \end{aligned} \tag{8}$$

where $\hat{D}_{td}(s)$ is the Laplace transformation of $\hat{d}_{td}(t)$. Thus, the output without time delay $Y_p(s)$ is the addition of $Y(s)$ and $G_0(s)\hat{D}_{td}(s)$.

$$Y_p(s) = G_0(s)\hat{D}_{td}(s) + Y(s) \\ \approx G_0(s)U(s) \tag{9}$$

## 2.2 Time delay compensation based ADRC

The output without time delay $Y_p$(s) and the input $u$(s) are used in ESO. Thus, the time delay compensation based ADRC is proposed as shown in Figure 3.

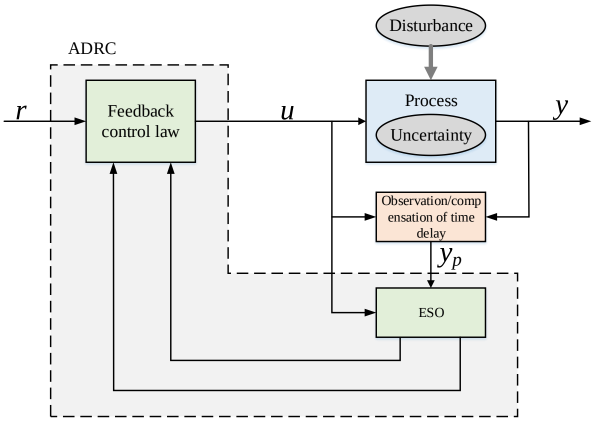



*Figure 3: Control structure of time delay compensation based ADRC*

The ADRC controller is then devised to track the reference and suppress the disturbance. Consider a nonlinear plant without time delay,

$$\dot{y} = bu + f(y) + d \tag{10}$$

where $f(\cdot)$ is the internal uncertainty, $d$ is the unknown external disturbance, $b$ is the input factor.
In ADRC, the lumped disturbance including the internal uncertainty and the unknown disturbance is estimated simultaneously via ESO. The augmented plant from (10) is

$$\begin{cases} \dot{y} = b_0 u + \sigma \\ \dot{\sigma} = h \end{cases} \Rightarrow \begin{cases} \dot{x} = Ax + Bu + E\sigma \\ y = Cx \end{cases} \tag{11}$$

where $b_0$ is the speculated value. The lumped disturbance is $\sigma = f(\cdot) + d + (b - b_0)u$, and is assumed to be differentiable. In the state space representation, $x = [x_1 \quad x_2]^T = [y \quad \sigma]^T$, $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} b_0 \\ 0 \end{bmatrix}, C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T$, $E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$. The ESO in ADRC is designed as

$$\begin{cases} \dot{z} = Az + Bu + L(y - \hat{y}) \\ \hat{y} = Cz \end{cases} \tag{12}$$

where $L$ is the gain of ESO, $z$ is the estimation of $x$. The final control law is

$$u = \frac{k_p(r - y) - z_2}{b_0} \tag{13}$$

# 3. Simulations and results

To verify the effectiveness of the proposed method, the typical first order plus dead time (FOPDT) model is used for simulation.

$$G(s) = \frac{6.31}{145s + 1} e^{-60s} \tag{14}$$

The model (14) can reflect the dynamics of fuel-power loop in a subcritical coal-fired boiler-turbine unit. Another three methods are compared in the section, i.e. the Smith predictor based ADRC (SP-ADRC) (Zheng and Gao, 2014), the delay designed ADRC (DD-ADRC) (Zhao and Gao, 2014), and the original ADRC (Zheng and Gao, 2014). The parameters of these controllers come from the literature accordingly.

The proposed time delay compensation based ADRC (TDC-ADRC) are tuned by bandwidth-parameterization (Zhiqiang, 2003), that are $b_0 = 8.35\times10^{-2}$, $\omega_c = 0.04$, $\omega_o = 0.15$. The simulation is assumed that (1) 0-25min is for setpoint tracking, (2) 25-50min is for disturbance rejection (the unknown disturbance *d* = -3kg/s), and (3) 5-75min is also for setpoint tracking, however, the time delay of the model (14) changes from 60s to 70s. Figure 4 shows the simulation results.

From 0-25min, it can be found that the original ADRC can hardly deal with time delay process, which has the largest settling time and overshoot. The other three methods have better performances and can overcome the effect of time delay. Particularly, in this time interval the proposed TDC-ADRC has the same results with SP-ADRC because TDC-ADRC is equivalent to the SP-ADRC when the time delay is nominal.

From 25-50min, it can be found that TDC-ADRC and SP-ADRC have better performance. DD-ADRC is slightly better than the original ADRC.

From 50-75min, it can be found that when the value of time delay changes, TDC-ADRC achieves the best performance. This is due to the fact that in TDC-ADRC the effect of time delay is estimated rather than the direct usage of time delay model in SP-ADRC.

For the dynamic model of fuel-power loop in a subcritical coal-fired boiler-turbine unit, its character coefficients, including the time delay, vary frequently due to the adjustments of operation conditions required by the grid. To achieve the better economic performance, the output power of the boiler-turbine unit should track the command from the grid promptly regardless of the unexpected disturbance and feature variation. The better adjustment ability implies that the coal-fired boiler-turbine unit can operate more economically, save more coal and accordingly reduce the emission of pollutants.

The simulations demonstrate that the proposed method is effective with regard to these requirements. What is more, the simple structure of the TDC-ADRC has the potential for implementing the method in the distributed control system of the real coal-fired power plant.

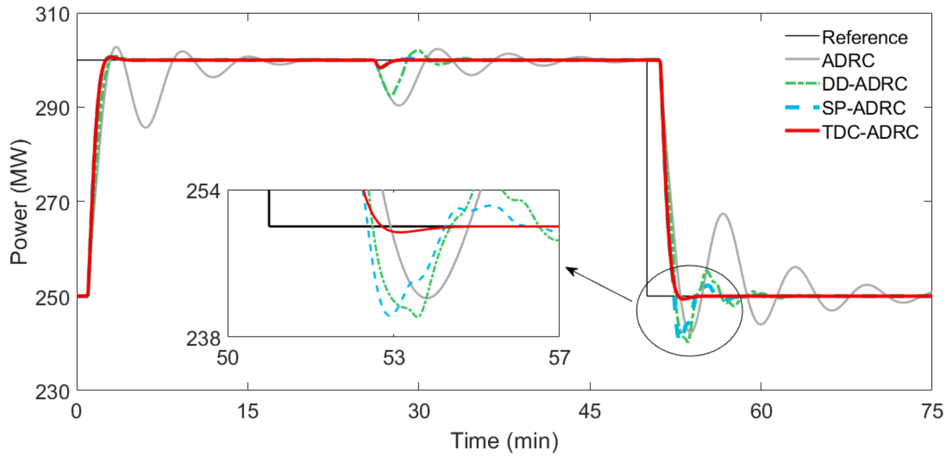



*Figure 4: Simulation of the fuel-power loop in boiler-turbine unit*

## 4. Conclusions

To deal with the issues of time delay and disturbance rejection in energy systems, the time delay compensation based ADRC is proposed in this research. The effect of time delay is regarded as disturbance and estimated and compensated by the designed structure. The method is particularly useful when the time delay changes. The effectiveness of the proposed method is validated through simulations on the boiler-turbine unit. Further research should focus on determining the stability region of the time delay observer and the ADRC controller.

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