

## Distributed Control System Applied in Temperatur Control by Coordinating Multi-loop Controllers

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### Abstract

*In Distributed Control System (DCS), multitasking management has been important issues continuously researched and developed. In this paper, DCS was applied in global temperature control system by coordinating three Local Control Units (LCUs). To design LCU's controller parameters, both analytical and experimental method were employed. In analytical method, the plants were firstly identified to get their transfer functions which were then used to derive control parameters based on desired response qualities. The experimental method (Ziegler-Nichols) was also applied due to practicable reason in real industrial plant (less mathematical analysis). To manage set-points distributed to all LCUs, master controller was subsequently designed based on zone of both error and set-point of global temperature controller. Confirmation experiments showed that when using control parameters from analytical method, the global temperature response could successfully follow the distributed set-points with 0% overshoot, 193.92 second rise time, and 266.88 second settling time. While using control parameters from experimental method, it could also follow the distributed set-points with presence of overshoot (16.9%), but has less rise time and settling time (111.36 and 138.72 second). In this research, the overshoot could be successfully decreased from 16.9 to 9.39 % by changing master control rule. This proposed method can be potentially applied in real industrial plant due to its simplicity in master control algorithm and presence of PID controller which has been generally included in today industrial equipments.*

**Keywords:** Distributed control system; System identification; Temperature control; Ziegler-nichols; Multi-loop PID controllers

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### 1. Introduction

Distributed Control Systems (DCS) is advance control method which can manages and coordinates many automation equipments, local/ single loop controllers and sensor networks. It is widely used in plant systems, -usually in process control such as temperature, pressure liquid level and flow,- which have constrains around distance, amount of plants and spreading of area. For hardware infrastructure, DCS involves high technology communication networks (such as fiber optic, FDI fieldbus, and Ethernet) and last update of information technology such as cloud computing [1].

DCS also provides solution for advance and complex industrial process, application of supervisory control, operator centric, enterprise-integrated information, and fast-complex-coordinated system [2]. Researches in DCS have been addressed to find effective coordinated algorithm. Nikolay et al. used DCS algorithm applied in mobile robot network. In their research, DCS was used to analyze environment circumstance to distribute important parameters e.g: radio signal, magnetic field, temperature and chemical concentration [3]. Liu & Yang used DCS algorithm to decrease time drift and propagation delay in Network Time Protocol (NTP).

Result of their experiment concluded that by using DCS algorithm (namely: Precise Clock Synchronization Algorithm), the accuracy could fulfill IEEE 1588 standard [4]. Garin and Schenato proposed Linear Consensus Algorithm to analyze frequently algorithms used in DCS, e.g: least squares, sensor calibration, vehicle coordination and Kalman filter, so that it can decide which method enabling to enhance system performance [5]. Liu proposed Particle Swarm Optimization applied in optimal scheduling to overcome multi-task in DCS. Simulation result showed that the proposed method could make DCS derive good performance index [6].

In DCS research area, PID controller is generally applied as sub-controllers executing master control command. This algorithm has been widely used due to its simplicity and

robustness [7,8]. In industrial point of view, PID controller is also practicable tools due to its availability in today industrial equipments such as some series of PLCs, DCS software, Advantech 6022, and popular software such as LabView and Matlab. Metcalf in [9] used PID controller as part of proposed DCS algorithm applied in a reactor hot water layer system. In this research, the author discussed about back-calculation anti-windup PID controller and safety system in large scale industry. Lombana and Di Bernardo used distributed PID controller in homogenous and heterogeneous network. They proved the proposed method by using state transformation and Lyapunov function applied in power-grid model [10].

From numerous published researches in DCS, in fact, they are difficult to realization due to high mathematical analysis [11,12]. Therefore this paper discusses several new issues, in term of feasibility to bring in industrial practice and case study in industrial process plant (temperature control system), which have not addressed yet in previous published papers [3-10]. In this research, DCS is applied to temperature control system influenced by three sub-systems (fan velocity, position of window, and local temperature control) which will be coordinated by master controller. To design each local control unit, analytical and experimental method are employed to derive PID control's parameters. In analytical method, the plant was firstly identified to derive its transfer function. Based on desired performances (% overshoot and rise time), the model is then used to find controller parameters which will be verified to all local control unit (LCU). On the other hand, the experimental method (Ziegler Nichols technique), which avoids mathematical analysis and widely used in industrial practice, is also employed to find PID control's parameters. In this method, the controller parameters are just a starting point so when they are applied some tuning is still needed. All LCUs are finally integrated and coordinated by proposed master control designed based on error and set-point of global temperature.

## 2. Experiment Setup

Figure 1 depicts three sub-systems (Velocity of the fan, position of the window, and local temperature control) which will be controlled by DCS. For each controller parameters of the sub-system, single loop PID controller will be employed and designed by using analytical and Ziegler-Nichols method. After designing local control parameters, master control will be designed to coordinate all three sub-controllers so that temperature set-point can be reached as fast as possible. All experiment setups are depicted in Figure 2.

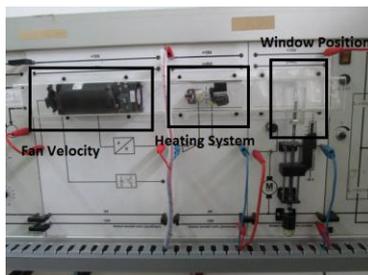


Figure 1. Sub-systems of DCS

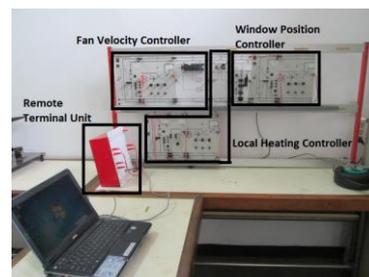


Figure 2. DCS with Remote Terminal Unit (RTU) and three sub-controllers

## 3. Controller Design

In the sub-controller design, analytical method is firstly applied to find PID parameters. In this section, system identification technique is firstly employed to derive plant model. On the other hand, because in industrial practice mathematical or analytical method is sometime avoided due to complexities or lack of mathematical background, reaction curve method (Ziegler-Nichols) is thus employed to derive PID controller parameters. In this method, set point and response are plotted together, which are subsequently –by using some procedure–used to find controller parameters. Master controller is finally designed by formulizing some rules based on position of error and global set-point.

### 3.1. Fan Velocity Controller

This plant consists of DC motor coupled with a fan. Transfer function of this plant was derived by applying identification toolbox in Matlab. Firstly, plant was set to open loop and then stored both set point and response data. The total amount of each input-output data are 3627 with sampling time 0.05 second. Because of the small size of DC motor, the influence of inductance (L) can be avoided so its model can be assumed as 1-st order equation 1.

$$P_{Fan} = \frac{1.247}{s + 1.302} \quad (1)$$

In this research, PI Controller was employed as fan velocity controller. equation 2 is the general equation of the proposed controller. With H is assumed 1, the overall transfer function of feedback control is equation 3 and equation 4.

$$C_{Fan} = \frac{K_p s + K_i}{s} \quad (2)$$

$$G_{Fan} = \frac{P_{Fan} C_{Fan}}{P_{Fan} C_{Fan} H + 1} \quad (3)$$

$$G_{Fan} = \frac{1.247(K_p s + K_i)}{s^2 + (1.302 + 1.247 K_p)s + 1.247 K_i} \quad (4)$$

From the equation 4, based on general equation of second order transfer function, both parameters (Kp and Kd) can be derived. The next step is to find  $\zeta$  and  $\omega_n$  based on the desired specifications: % overshoot is 5 % or less ( $M_p=0.05$ ); rise time ( $t_r$ ) is 1 second. With derived control parameters ( $K_p=2.5278$  and  $T_i=0.3032$ ), It shows that, as depicted in Figure 5, the designed parameters could make the response follow the set point properly.

This research also employed Ziegler Nichols type-2 to find PID controller parameters. In this method, system was set to closed loop and varied the gain (Kcr) so that the response start to periodically sustained oscillation as shown in Figure 6. The critical gain (Kcr) and critical phase (Pcr) were then used to determine the value of Kp, Ti, and Td [15]. In this experiment, simulink Matlab was used to plot both response and set point. From the observation, it showed that the real time clock was not same as Matlab time (5 shown in Matlab equal to 2 second) so that conversion calculation was needed [13,15]. After conversion calculation (with  $K_{cr}=18.6$  and  $P_{cr}=0.44$ ), the control parameters ( $K_p=11.16$ ,  $T_i=0.22$ ,  $T_d=0.055$ ) were then applied to plant. In this method, the derived parameters are just approximation, it still needs to be tuned based on tuning rule in Table.1. The final PID parameters are  $K_p=11.2$ ,  $T_i=5$ ,  $T_d=0$  giving good response as depicted in Figure 7.

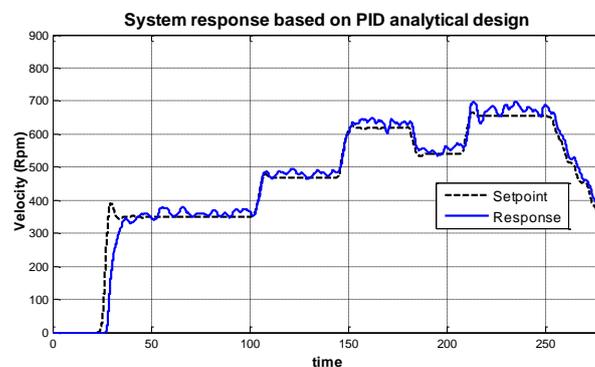


Figure 5. System response based on PID analytical design

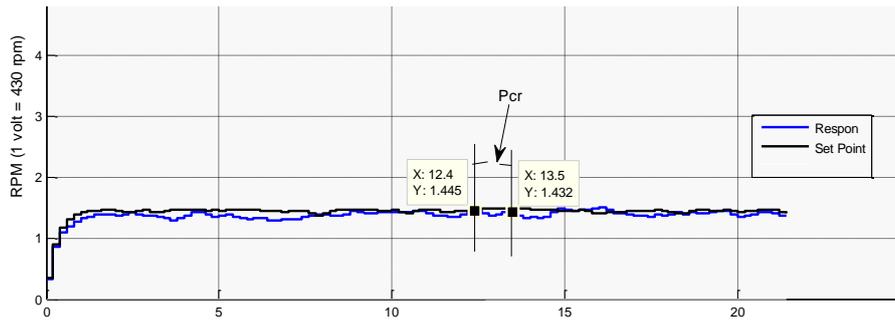


Figure 6. Controller design by using Ziegler Nichols type-2.

Table 1. Tuning Rule.

Parameters	Rise time	Overshoot	Settling time	Steady-State error
Kp	Decrease	Increase	Minor Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Minor Change	Decrease	Decrease	Minor change

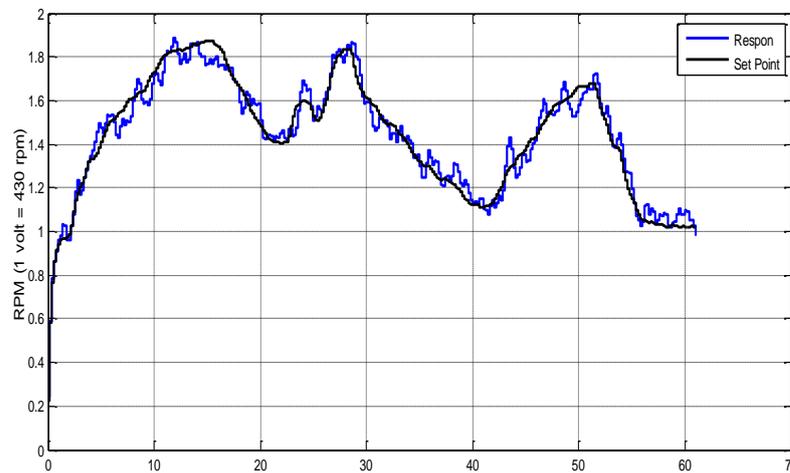


Figure 7. Fan Velocity Response

### 3.2. Local Temperature Controller

Local temperature controller was designed to control internal dynamic of local heating system. As previous procedure, plant model was firstly identified so that, regarding to desired specification, the derived transfer function in equation 5 could be used to find PID controller parameters. The raw data needed for identification were taken from open loop response of set-point and output. Because the heater lamp and the heated area are small, the heating system was assumed as 1-st order without delay.

$$P_{Tem} = \frac{0.000375}{s + 0.001418} \tag{5}$$

In this research, PID Controller was employed as local temperature controller. Equation 6 is the general equation of the proposed controller.

$$C_{Temp} = \frac{Kd s^2 + Kp s + Ki}{s} \tag{6}$$

Based on desired specification (% overshoot is 5 % or less [ $M_p=0.05$ ]; and rise time [ $t_r$ ] is 30 second), we can derive  $\zeta=0.6907$  and  $\omega_n=0.1075$  so that desired pole location ( $s_1$ ) is defined as equation 7 [14] can be calculated.

$$s_1 = -\zeta\omega_n + \omega_n\sqrt{1-\zeta^2}j \quad (7)$$

$$s_1 = -0.0742 + 0.0777j, \quad |s_1|e^{j\beta} = 0.1074e^{j133.68^\circ}$$

with H is assumed as 1,

$$G(s_1)H(s_1) = \frac{0.000375}{(-0.0742 + 0.0777j) + 0.001418}, \quad G(s_1)H(s_1) = \frac{0.000375}{-0.0728 + 0.0777j}$$

$$|G(s_1)H(s_1)| = |G(s_1)H(s_1)|e^{j\psi} = 0.0035e^{j179.1821^\circ}$$

Equation 8 and 9 are the equations to find  $K_p$  and  $K_d$ . Because there are three searched variables ( $K_p$ ,  $K_i$ ,  $K_d$ ), so it can be manually assumed one (in this research  $K_i=4$ ) so  $K_p$  and  $K_d$  can be derived.

$$K_p = \frac{-\sin(\beta + \psi)}{|G(s_1)H(s_1)|\sin(\beta)} - \frac{2K_i\cos(\beta)}{|s_1|} \quad (8)$$

$$K_d = \frac{\sin(\psi)}{|s_1||G(s_1)H(s_1)|\sin(\beta)} - \frac{K_i}{|s_1|^2} \quad (9)$$

with  $|G(s_1)H(s_1)| = 0.0035$ ,  $|s_1| = 0.1074$ ,  $\beta = 133.68^\circ$  and  $\psi = 179.1821^\circ$ , the derived controller parameters ( $K_p=344.6436$ ,  $T_i=86.1609$  and  $T_d=0.8629$ ) were then applied to real plant as depicted in Figure 8.

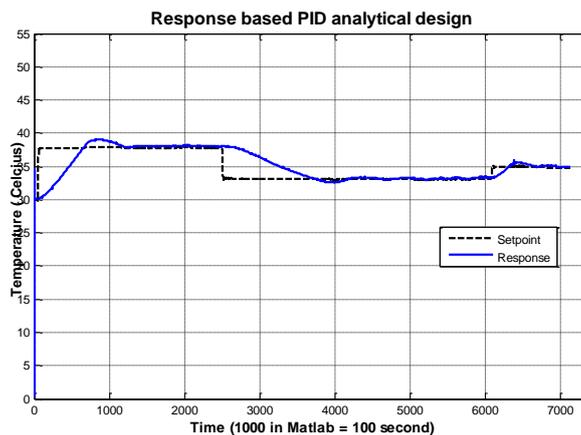


Figure 8. Local temperature control by using PID analytical design

This research also employed Ziegler Nichols type-1 to find PID controller parameters. In this method, system was set to open loop and plotted plant response against given set point as shown in Figure 9. From the observation, it showed that time in Matlab needs to convert to real time clock (500 shown in Matlab is equal to 45.57 second). After conversion calculation, the needed parameters, L and T, were derived and then used to calculate PID controller

parameters: 7.5, 33.56, and 8.39 for  $K_p$ ,  $T_i$ , and  $T_d$  respectively. These parameters were then applied to the plant and the result shown in Figure 10.

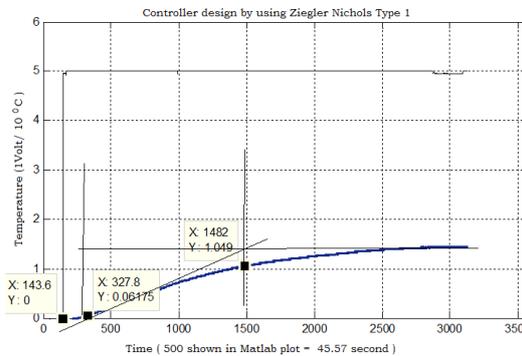


Figure 11. Controller design by using Ziegler Nichols type-1.

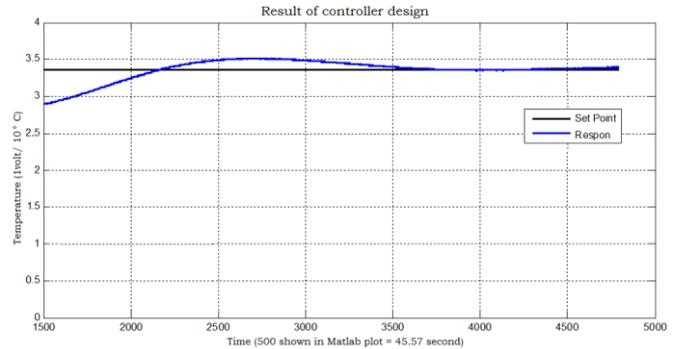


Figure 10. Result of controller design.

### 3.3. Window Position Controller

Together with fan velocity, the position of the window will also influence the rate of temperature change. In this controller design, because the plant is n-order type-1 (position is the result of motor velocity integration), integral part of the controller was thus eliminated. Differential part was also eliminated due to noise of the feedback so that the controller was only proportional controller, which was then designed by manually tuning the proportional gain ( $K_p=50$ ).

### 3.4. Master Controller

Master controller is designed to manage three sub-controllers based on set-point and error of global temperature. Because each local control unit needs time to give response, the applied rules in master controller were set linear so that distributed set-points from master controller could be followed properly. Figure 11 is diagram block for overall system. Equation 10 is set of the rules for Fan Velocity Set-point (FVS [in RPM unit]), which is designed based on condition of global temperature error ( $e$ ), and Window Position Set point (WPS [unit in cm]) which is designed based on Global Temperature Set-point (GTS).

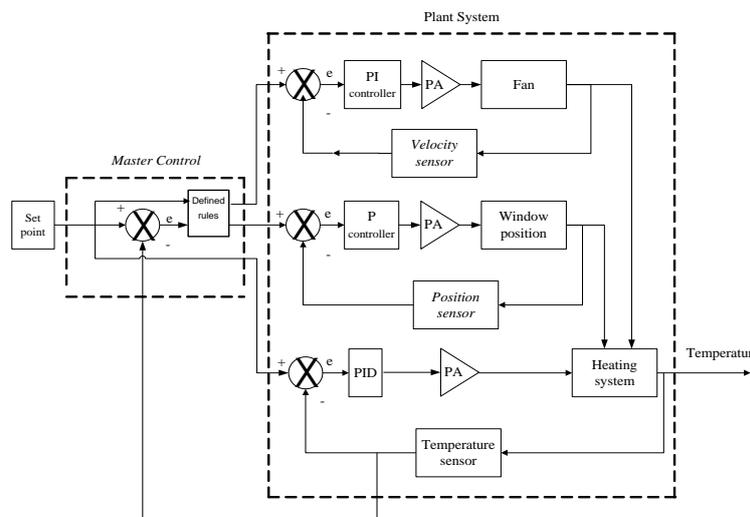


Figure 11. Diagram block of DCS and Master Controller

$$\text{FVS} = \begin{cases} 0, & e > -3 \\ 860, & -10 < e \leq -3 \\ 1720, & -20 < e \leq -10 \\ 2580, & -30 < e \leq -20 \\ 3440, & -65 < e \leq -30 \end{cases} \quad \text{WPS} = \begin{cases} 2, & 0 \leq \text{GTS} < 25 \\ 4, & 25 \leq \text{GTS} < 30 \\ 5, & 30 \leq \text{GTS} < 40 \\ 6, & 40 \leq \text{GTS} < 60 \\ 7, & 60 \leq \text{GTS} < 65 \end{cases} \quad (10)$$

#### 4. Result and Discussion

In verification experiment, Matlab 2013A was employed to apply master controller algorithm. Firstly, control parameters resulted from analytical design was applied to LCUs. Figure 12 depicts three responses of global temperature, fan velocity, and window position set-point. It shows 0%, 193.92 second, and 266.88 second for % overshoot, rise time, and settling time, respectively. The response of fan velocity controller could successfully follow the defined rule in master control. In the window position system, the set point could also change according to temperature set point value. In this study, the defined window position is not only accelerates temperature change but also keeps the temperature with efficient heating power. The second step is to verify local control parameters which were designed based on experimental method. Figure 13 is the response while using this experimental technique. The result shows that the global temperature controller could give response with presence of overshoot (16.9%), but has less rise time and settling time (111.36 and 138.72 second).

To overcome the presence of overshoot, it could be enhanced by changing master control rule in equation 10. Figure 14 shows the response after changing the master control rule. From 7320-th second, the overshoot could be successfully decreased from 16.9 to 9.39 %. With this method, smaller overshoot can be also derived by changing error zone limit (e.g: bigger than -0.5) so that when response starts to increase more than the limit, fan will automatically start to cool it down.

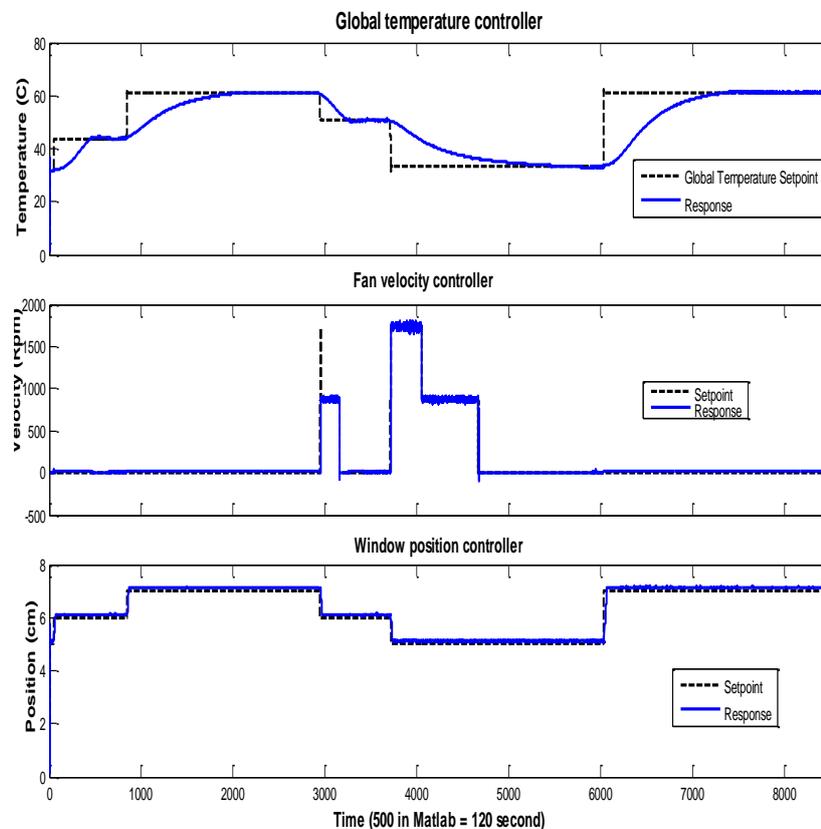


Figure 12. Result of DCS while using controller parameters from analytical technique.

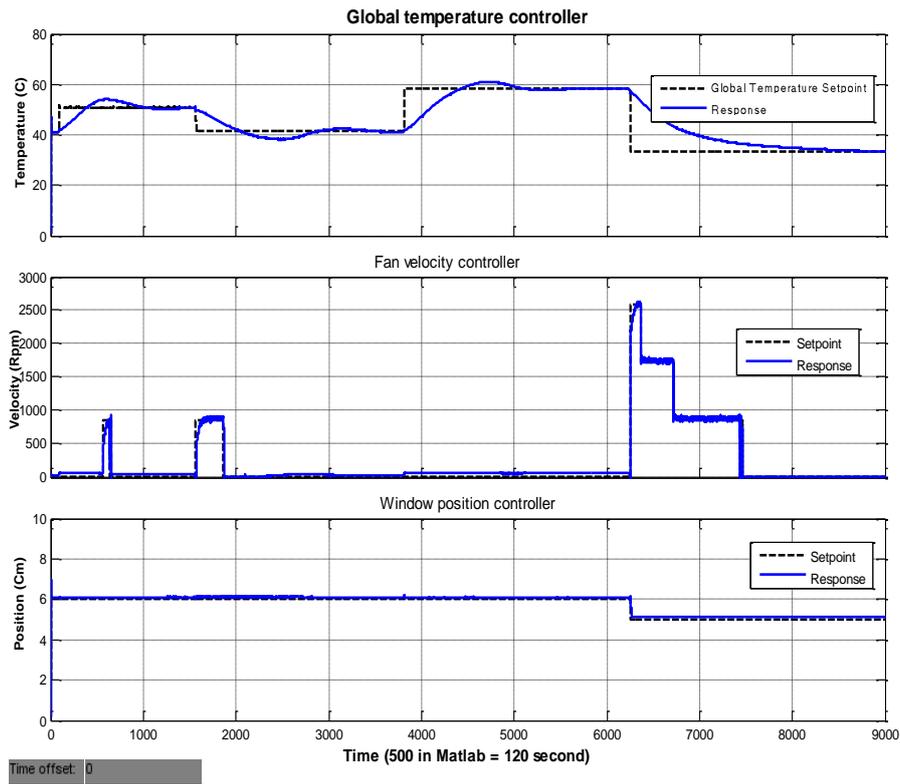


Figure 13. Result of DCS while using controller parameters from experimental technique.

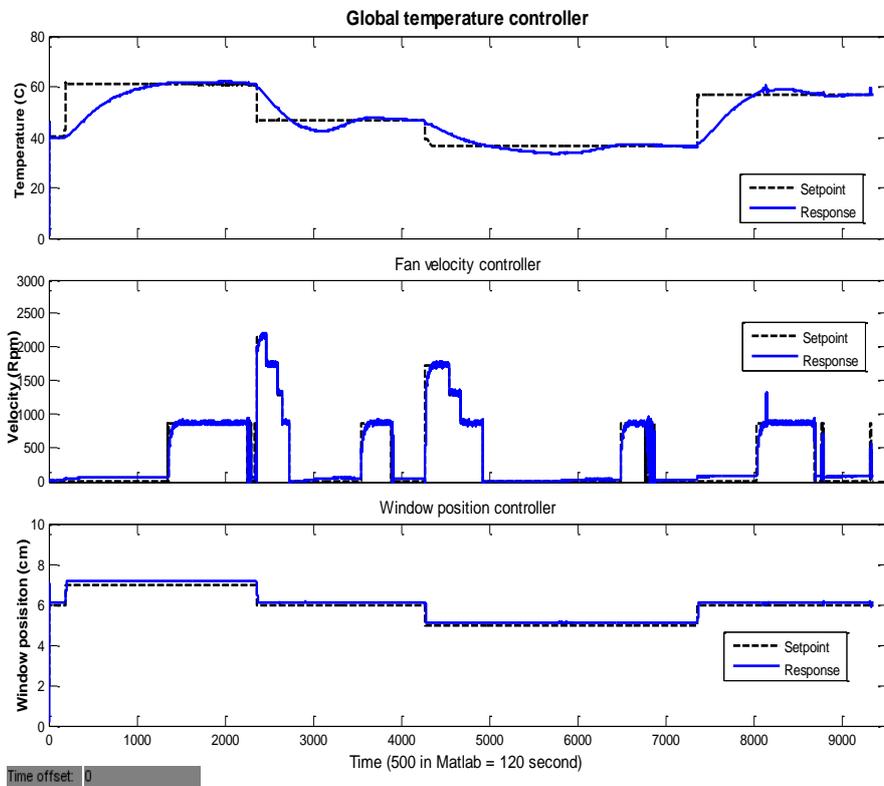


Figure 14. Result of DCS after changing master control rule.

## 5. Conclusion

In this paper, DCS method was applied in temperature control system by coordinating three Local Control Units (LCUs). To design controller parameter of each LCU, both analytical and experimental (Ziegler-Nichols) method were employed. Master controller, which was designed based on zone of both error and set-point of global temperature controller, was subsequently applied to manage three LCUs. Confirmation experiment showed that control parameters designed from analytical method could follow distributed set-points with 0% overshoot. On the other hand, control parameters designed from experimental method could also follow the distributed set-point with presence of overshoot but smaller rise time and settling time. In this research, this problem could be successfully enhanced by changing the rule of master control so that the overshoot could be decreased from 16.9 to 9.39 %. The method can be potentially applied in real industrial plant due to its simplicity in master control algorithm and presence of PID controller which has been generally included in today industrial equipments.

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