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# Design and Simulation of a Robust Combustion Control System for a Steam Power Plant Using MATLAB Simulink

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***Abstract:*** *Steam power plants are extensively utilised worldwide for electricity generation and whose operation efficiency should be improved to make better utilisation of fossil fuels. Inside a steam power plant, the combustion system is probably the most imperative system to be controlled since it guarantees the effective and secure operation of the boiler. In this paper, firstly, the block diagram and corresponding transfer functions of the combustion system were built and assumed. Then, the conventional and fuzzy PID controllers were designed and applied to control the boiler combustion system. Through the simulation using MATLAB Simulink, the closed-loop responses of the conventional PID and the fuzzy controller were obtained and compared. Furthermore, the robustness of the fuzzy PID controller was tested and verified. The results show that the overall performance of fuzzy PID controller is more excellent than the conventional one. Additionally, it is also proven that the fuzzy PID controller possesses outstanding robustness, and it can handle quite well with the disturbances appearing in the system and the uncertainties that occurred in system modelling, which is rather advantageous and practical in a steam power plant.*

***Keywords:*** *Steam power plant, Combustion control system, Robust control method, MATLAB Simulink*

## 1. Introduction

First of all, steam power plants, powered by fossil fuels, are extensively and maturely utilised worldwide for electricity generation. Regardless of the promotion of renewable energies, due to the immaturity of these technologies, the predomination of conventional steam power plants will not be replaced in the foreseeable future [1], thus its operation efficiency should be improved to make better utilisation of fossil fuels. Then, inside a steam power plant, the combustion system is probably the most imperative system to be controlled since it guarantees the effective and secure operation of the boiler [2]. Consequently, it is of great importance to enhance this combustion system’s performance, which can increase the efficiency and safety of the whole plant.

Furthermore, the robust control strategy can minimise or eliminate the uncertainty of the system, and it is designed to function properly even if unknown parameters or disturbances are found within the system. The robust controllers chosen for the system are the conventional proportional-integral-derivative (PID) controller which is commonly employed in the practical control engineering field, and the fuzzy PID controller which is a combination of the conventional PID controller and the advanced fuzzy logic theory [3]. Finally, MATLAB Simulink is an effective and easy-to-use software for implementing the design and simulation of the system. Therefore, this paper mainly concentrates on designing and simulating a robust combustion control system for a steam power plant using MATLAB Simulink [4].

## 2. Methodology

### *2.1. Mathematical Modelling*

The boiler combustion control system in this paper is considered to contain one subsystem, called the fuel regulating subsystem, which is probably the most vital part, since the fuel regulating subsystem controls the fuel flow to maintain the generated heat which is supplied to the boiler, and thus stabilises the steam pressure [2]. Additionally, the combustion control main system controls the steam pressure so that there is enough thermal energy supplied to meet the needs of the turbine to generate adequate electricity.

In order to create a block diagram, all the components of the control system were specified, and the nature of inputs, outputs, actuators, processes or plants, sensors, and disturbances were also specified. After creating the block diagram, some transfer functions were assumed based on Reference [5, 6]. The block diagram of the system is shown in Figure 1, and the transfer functions are also labelled besides each block.

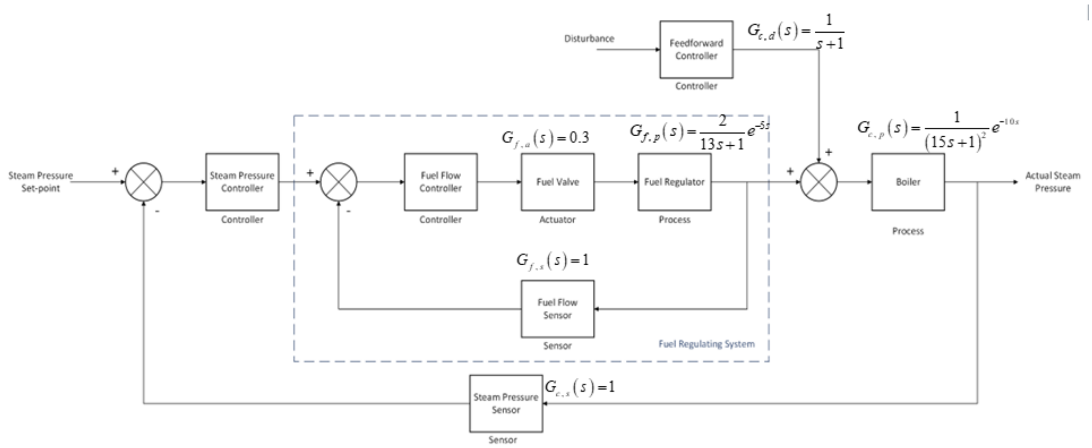


*Figure 1: Block diagram and transfer functions of the combustion control system.*

### *2.2. Conventional PID Controller*

The robust controllers chosen for the system are the conventional PID controller and the fuzzy PID controller. The conventional PID controller is extensively applied in various kinds of control systems and has great robustness. The Ziegler-Nichols (Z-N) ultimate gain tuning method [7] was utilised to tune the subsystem's PI controller and the main system's PID controller. In addition, the transfer functions of the PI and PID controllers are shown in Equation (1) and Equation (2).

$$G_{PI}(s)=K_p+\frac{K_i}{s}=K_p\left(1+\frac{1}{T_i s}\right) \tag{1}$$

$$G_{PID}(s)=K_p+\frac{K_i}{s}+K_d s=K_p\left(1+\frac{1}{T_i}s+T_d s\right) \tag{2}$$

$$\text{where } \; T_i=K_p/K_i \; \text{ and } \; T_d=K_d/K_p\,. \tag{3}$$

The following procedures were adopted to accomplish the Z-N ultimate gain tuning method. Firstly, the Bode diagram of the open-loop system was utilised to find out the gain margin of the system, and the gain margin is the very ultimate gain to be evaluated. Then, the system was connected as a closed-loop feedback system with a proportional controller. After that, the oscillation period could be obtained by determining the period of the closed-loop response. Finally, by using the Z-N tuning table, the PID parameters, namely, $K_p$, $T_i$, and $T_d$, could be calculated [8]. The conventional PID controllers were also built using the determined PID parameters, as shown in Figure 2 and Figure 3.

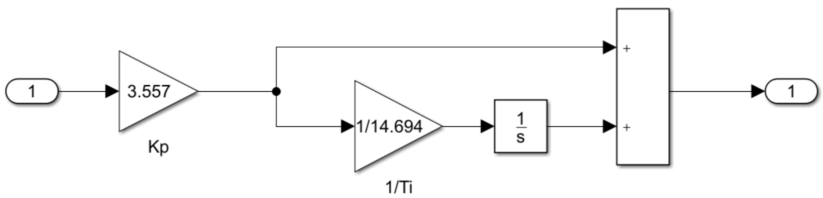


*Figure 2: Conventional PI controller of the fuel regulating subsystem.*

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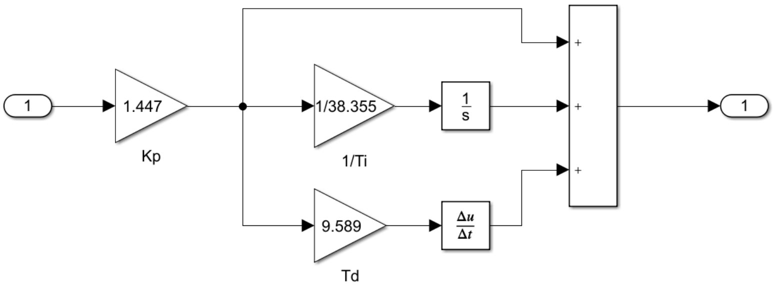


*Figure 3: Conventional PID controller of the combustion control system.*

### *2.3. Fuzzy PID Controller*

The fuzzy PID controller consists of two components: a traditional PID controller and a fuzzy inference system. The following steps are required to design and simulation a fuzzy PID controller. To begin with, the input and output variables of the fuzzy inference system (FIS) should be determined. The input variables are the error ($e$) and the error's rate of change ( $\dot{e}$ ), and the output variables are three PID parameters ($K_p$, $K_i$, and $K_d$).

Then, the triangular-shaped membership functions of these fuzzy variables should also be determined for the fuzzification and defuzzification stage afterwards. As shown in Figure 4, all the forenamed variables use an identical set of seven triangular membership functions, named after linguistic variables (NB: Negative Big, NM: Negative Medium, NS: Negative Small, ZE: Zero, PS: Positive Small, PM: Positive Medium, and NB: Negative Big), within the range of -6 to 6.

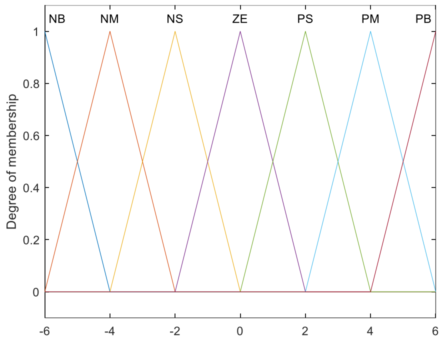


*Figure 4: Membership functions of $e$, $\dot{e}$, $K_p$, $K_i$, and $K_d$.*

After that, the fuzzy rules should be specified, in the form of "If – Then" and using the linguistic variables. For example, this is a typical fuzzy rule: "if $e$ is NB and $\dot{e}$ is NB, Then $K_p$ is PB, $K_i$ is NB, and $K_d$ is PS". The fuzzy rules of each output ($K_p$, $K_i$, and $K_d$) associated with the two inputs ($e$ and $\dot{e}$) are listed in Table 1 – Table 3 respectively.

*Table 1: Fuzzy rules of $K_p$.*

| $K_p$ | | $\dot{e}$ NB | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| $e$ | NB | PB | PB | PM | PM | PS | ZE | ZE |
| | NM | PB | PB | PM | PS | PS | ZE | NS |
| | NS | PM | PM | PM | PS | ZE | NS | NS |
| | ZE | PM | PM | PS | ZE | NS | NM | NM |
| | PS | PS | PS | ZE | NS | NS | NM | NM |
| | PM | PS | ZE | NS | NM | NM | NM | NB |
| | PB | ZE | ZE | NM | NM | NM | NB | NB |

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*Table 2: Fuzzy rules of $K_i$.*

| $K_i$ | | | | | $\dot{e}$ | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | ZE | PS | PM | PB |
| | NB | NB | NB | NM | NM | NS | ZE | ZE |
| | NM | NB | NB | NM | NS | NS | ZE | ZE |
| | NS | NB | NM | NS | NS | ZE | PS | PS |
| $e$ | ZE | NM | NM | NS | ZE | PS | PM | PM |
| | PS | NM | NS | ZE | PS | PS | PM | PB |
| | PM | ZE | ZE | PS | PS | PM | PB | PB |
| | PB | ZE | ZE | PS | PM | PM | PB | PB |

*Table 3: Fuzzy rules of $K_d$.*

| $K_d$ | | | | | $\dot{e}$ | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | ZE | PS | PM | PB |
| | NB | PS | NS | NB | NB | NB | NM | PS |
| | NM | PS | NS | NB | NM | NM | NS | ZE |
| | NS | ZE | NS | NM | NM | NS | NS | ZE |
| e | ZE | ZE | NS | NS | NS | NS | NS | ZE |
| | PS | ZE | ZE | ZE | ZE | ZE | ZE | ZE |
| | PM | PB | NS | PS | PS | PS | PS | PB |
| | PB | PB | PM | PM | PM | PS | PS | PB |

Furthermore, the results obtained after the fuzzy rules inferencing are called fuzzy values. Notwithstanding, general actuators and plants can only accept a crisp value as a signal, which require a process named defuzzification. The defuzzification method chosen is centroid defuzzification method, which returns the fuzzy rule set's centre of gravity along the *x*-axis.

Last but not least, the inputs and outputs are in the range of [-6, 6], but the actual inputs of the FIS might be too small, so the inputs should be multiplied by quantisation factors before feeding into the FIS. In contrast, the outputs of the FIS are too large for the conventional PID controller and should be multiplied by scaling factors before sending into the traditional PID controller. Furthermore, the Z-N tuned PID parameters in Subsection 2.2 ($T_i$ and $T_d$) should be converted into $K_i$ and $K_d$ ones using Equation (1) and Equation (2) and added to the outputs as biases.

The Simulink block diagrams of the fuzzy PI controller for the fuel regulating subsystem and the fuzzy PID controller for the main combustion control system are shown in Figure 5 and Figure 6. For the fuzzy PI controller, the inputs of the fuzzy system are the error and the error's rate of change, and they have to go through a saturation block, which can limit their values into the range of [-6, 6]. Then, after the fuzzy inferencing system, three PID parameters, $K_p$, $K_i$, and $K_d$ are produced.

However, the PI controller only requires $K_p$ and $K_i$,, therefore the first two outputs will be used. Before they are utilised as the parameters for a conventional PI controller, they have to be multiplied by scaling factors and added by the Z-N tuned parameters. After that, the error is multiplied by the processed $K_p$, the integral of the error is multiplied by the processed $K_i$, and they are finally summed together as a control signal.

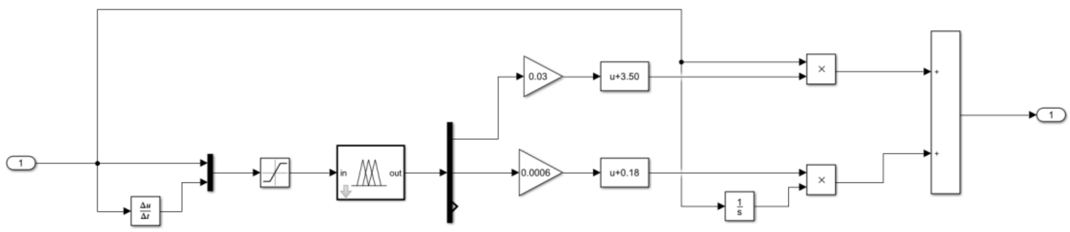


*Figure 5: Fuzzy PI controller for the fuel regulating subsystem.*

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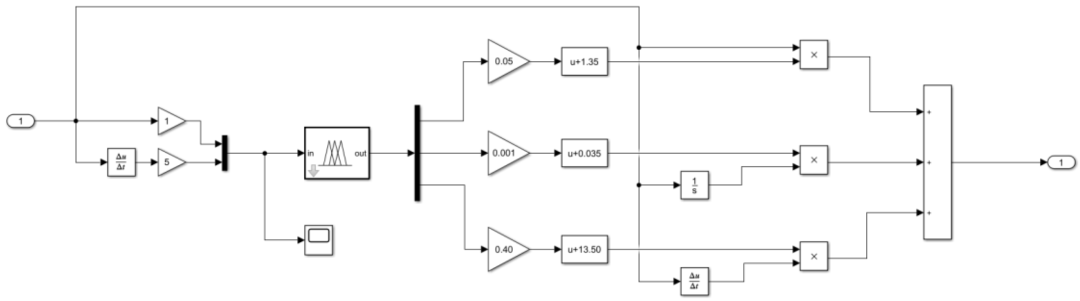


*Figure 6: Fuzzy PID controller for the combustion control system.*

Analogously, the design process of the fuzzy PID controller is quite similar to the aforementioned fuzzy PI controller. The inputs are multiplied by quantisation factors, and the outputs are multiplied by scaling factors and added by the Z-N tuned parameters. Finally, the processed $K_p$, $K_i$, and $K_d$ can be used for the parameters of a conventional PID controller. Therefore, these fuzzy PID controllers can then be utilised to control the systems, respectively.

## 3. Results and Discussion

To simulate the combustion control system in Simulink, first of all, the combustion system was connected using the predetermined block diagram and transfer functions. After that, traditional PID controllers and fuzzy PID ones were configured and utilised to control the system. Besides, the set-point of the steam pressure was 5MPa. The simulation results are shown in Figure 7. Compared to the conventional PID, the fuzzy PID reduces the overshoot and undershoot of the main system, which is less aggressive. Additionally, although the fuzzy PID's settling time and rise time are somewhat longer than those of the conventional PID, it exhibits much fewer oscillations, which demonstrates that the fuzzy PID has better robustness and damping characteristics.

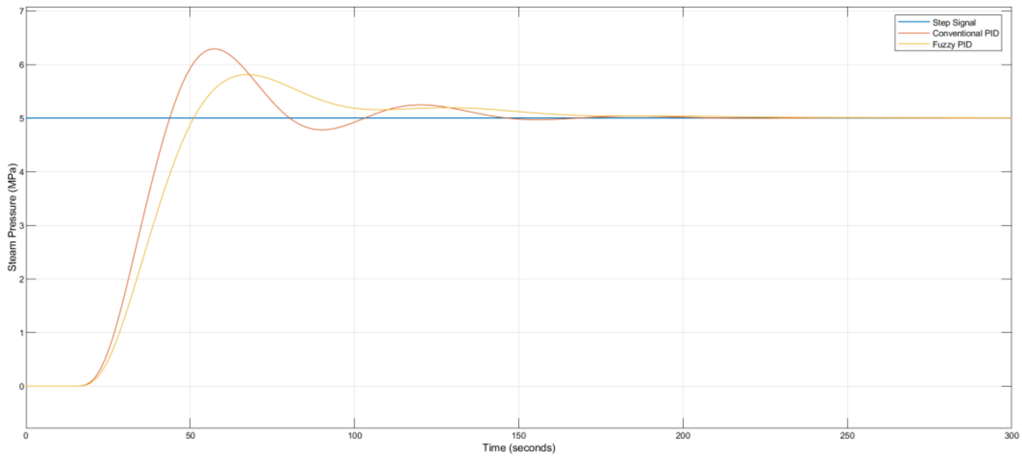


*Figure 7: Closed-loop step responses of conventional PID and fuzzy PID.*

Furthermore, there may be various kinds of disturbances in a real-world steam power plant. In order to evaluate the disturbance rejection ability of the fuzzy PID controller, a step-change signal, whose amplitude is 0.5 (10% of the input signal), was added to the system at the time of 300 seconds, as a disturbance signal. The corresponding closed-loop response curve is shown in Figure 8. It can be seen that when the disturbance signal occurs, there is a small overshoot appearing in the curve and the system responds relatively fast to the occurring disturbance, which indicates that the fuzzy PID controller can resist the disturbance signal well.

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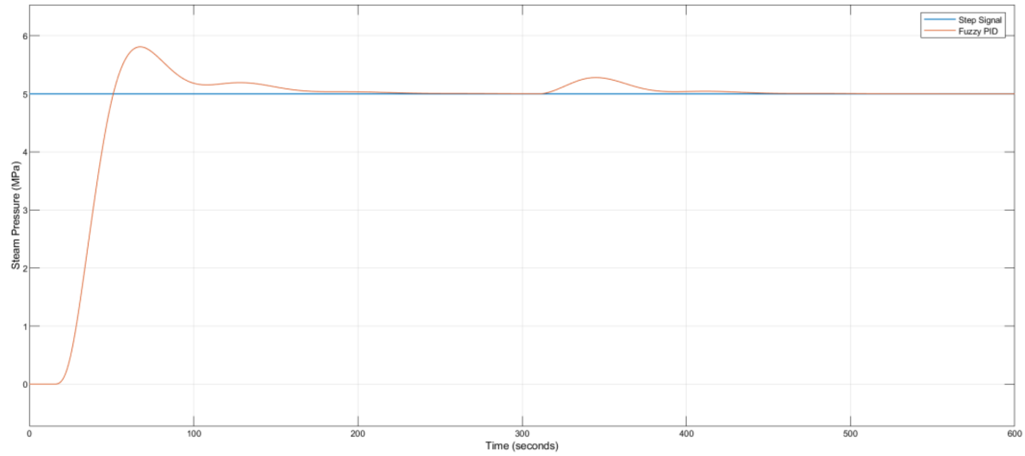


*Figure 8: Closed-loop step responses of fuzzy PID with disturbance applied.*

Last but not least, in an actual steam power plant, the obtained transfer functions are not always accurate, and there may be some errors with the parameters of the transfer functions. Therefore, the robustness of the combustion system was verified by varying some of the parameters in the transfer function of the boiler process, and running the simulation again to check whether the system remains stable or not. The corresponding results are shown in Figure 9, which reveal that using the fuzzy PID, the system can remain stable with the variations of the parameters in the transfer functions, and it also demonstrates the strong ability of disturbance rejection. Consequently, for a steam power plant, this method is quite advantageous and practical since it can function well regardless of the uncertainties appearing in transfer functions.

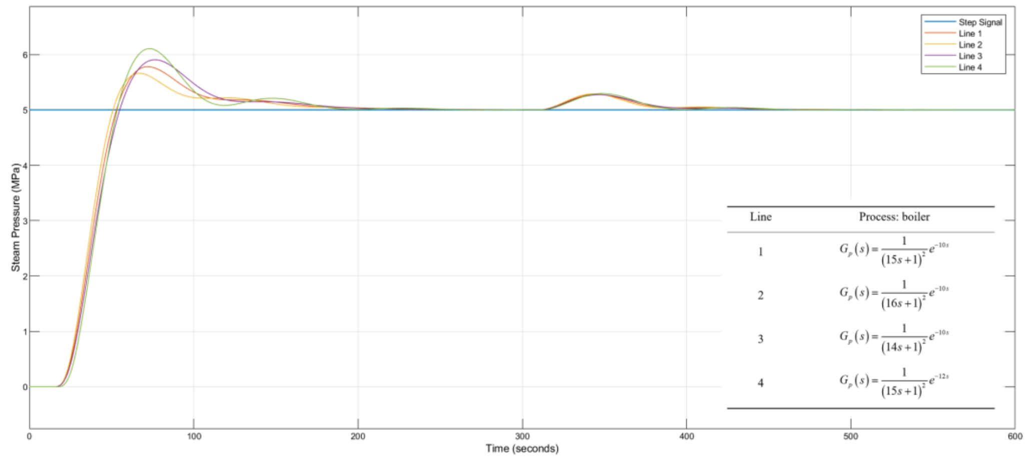


*Figure 9: Closed-loop step responses of fuzzy PID with different parameters.*

## 4. Conclusions

In this paper, the block diagram of the combustion system was initially created, and the transfer functions for the components were assumed. Then, the combustion control system was controlled by utilising a conventional PID controller and a fuzzy PID controller separately to compare and analyse the dynamic performance. It is concluded that the fuzzy PID control's overall performance is better than conventional PID control.

Moreover, the principle and theory of fuzzy control were first introduced, which laid a solid foundation for designing a fuzzy PID controller afterwards. Then, through Simulink simulation, the closed-loop responses of the two control methods were compared and analysed. It is concluded that the fuzzy PID control's overall performance is better than conventional PID control. Furthermore, it is proven that the fuzzy PID control has outstanding robustness. It can also deal with the disturbances appearing within the system and the uncertainties that occurred in system modelling as well, which is rather advantageous and practical in a steam power plant.

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**References**

*[1] International Energy Agency, Key World Energy Statistics, Paris: International Energy Agency, 2021.*
*[2] X. Wu, J. Shen, Y. Li, and K. Y. Lee, "Steam Power Plant Configuration, Design, and Control," Wiley Interdisciplinary Reviews: Energy and Environment, vol. 4, no. 6, pp. 537-563, 2015.*
*[3] M. Petrov, I. Ganchev, and A. Taneva, "Fuzzy PID Control of Nonlinear Plants," Proceedings of First International IEEE Symposium Intelligent Systems, vol. 1, pp. 30-35, 2002.*
*[4] L. Keviczky, R. Bars, J. Hetthéssy, and C. Bányász, "Introduction to MATLAB," Control Engineering: MATLAB Exercises, pp. 1-27, Singapore: Springer, 2019.*
*[5] Y. Li, "Modelling and Simulation of Boiler Combustion Process Control System," Heilongjiang Science and Technology Information, no. 33, pp. 143-144, 2015.*
*[6] J. Zhou, Q. Fang, and D. Wang, "Simulation of Combustion Process Control System Based on MATLAB/ Simulink," Journal of Zhengzhou University (Engineering Science), vol. 33, no. 2, pp. 51-54, 2012.*
*[7] J. G. Ziegler, and N. B. Nichols, "Optimum Settings for Automatic Controllers," Transactions of the American Society of Mechanical Engineers, vol. 64, no. 11, pp. 759-768, 1942.*
*[8] K. Ogata, "PID Controllers and Modified PID Controllers," Modern Control Engineering, pp. 567-647, Upper Saddle River: Pearson, 2010.*