Modeling and Simulation of The Source Measure Unit Based on Simulink

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ABSTRACT

Source measure unit (SMU) is a comprehensive instrument that provides functions such as measuring and supplying voltage and current sources. As the electronics research industry increases its requirements for product measurement and power supply, there is an urgent demand for better performance of the SMU control system. Based on the high cost and difficulty of entity optimization, this paper proposes the utilization of circuit analysis and Simulink to model and simulate the control system. Based on the foundation of PID control, the role of each control link is discussed in this paper. The simulation results show that PID control module can effectively optimize the performance of the SMU transient response by adjusting PID parameters under the input disturbance. On the basis of Simulink model, it is more convenient to improve the SMU and obtain a stable signal for the device under test, so that the SMU can better serve the electrical test field.

KEYWORDS

SMU, Circuit analysis, Simulink, PID control, Input disturbance

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1 INTRODUCTION

Source measure unit (SMU) is a high-precision instrument, which provides millivolt level voltage and microamp level current, measures voltage and current and so on [1]. And these comprehensive functions also make it widely used in testing electronic instrument and other fields [2].

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The process of researching and improving the SMU control systems requires not only theoretical analysis and calculations, but also performance researches. However, it is a difficult way to directly use entity for testing, which is expensive and time-consuming. The test condition of the parameters is dissatisfactory and there is a high risk of damaging the instrument. As a result, model research is necessary. And the physical model of the SMU is complex in structure, costly to set up in terms of time, money and material resources, and not very repeatable. Therefore, in response to the urgent demand to research and improve SMU control systems, building a mathematical model is a cost-effective way.

2 MODELLING METHODS FOR ELECTRICAL AND ELECTRONIC SYSTEM

Using mathematical model to simulate the electronic and electrical system is able to quantitatively describe the relationship between each link in the system, and conduct an economical, convenient, intuitive and rapid research on its static and dynamic characteristics. At present, there are various methods available for modelling a range of electrical and electronic systems like SMUs, such as modeling by frequency response, modeling by system identification, modeling by Simulink, etc.

2.1 Modeling by Frequency Response

For electrical and electronic systems that can use sinusoidal AC signals as input, the principle of frequency response can be used to analyze and model the system in terms of response curves.

In the process of changing the frequency of the input, the waveform information of the corresponding output is recorded to obtain the logarithmic frequency characteristic of the system [3]. Based on the curve image, the cut-off frequency, corner frequency, poles and zeros of the system are obtained by graphical method, and the system transfer function is calculated. For example, the pole is known to be the point at which the X-axis coordinate of the corner frequency decreases by -3db every time, while the law of the zero point is the opposite of the pole [4]. Assuming that the gain of a system is K, and zeros and poles derived from the corner frequency are z_i and p_j respectively, the transfer function of the system zero-pole gain model can be obtained as follows:

$$G(s) = K\frac{(s-z_1)(s-z_2)...(s-z_m)}{(s-p_1)(s-p_2)...(s-p_n)} \tag{1}$$

2.2 Modeling by System Identification

System identification is a methodology for constructing the system mathematical models using measurements of the input and output signals of the system. Compared with other modeling methods, system identification does not require knowledge of the internal structure and operation mechanism [5].

When using the method to build a model, users are required to measure the input and output signal or frequency domain of a system and select the structure of a model. And the next step is estimating and adjusting the parameters in the chosen structure. Finally, the model is built through which the estimated parameters is adequate for users' application needs [6].

System identification can be divided into offline identification and online identification. The online identification method requires less computer memory and is suitable for real-time control, but the accuracy of parameter estimation is relatively low [7]. Although offline identification requires a large amount of data storage and computation, the accuracy of parameter estimation is higher. When modeling by system identification, it is necessary to elect an appropriate identification method according to the experimental requirements.

2.3 Modeling by Simulink

As one of the best numerical computing software in the world today, Matlab provides programming and numerical computing capabilities to support data analysis, algorithm development and modeling. These powerful functions make Matlab the most widely used computer-aided design and control system simulation software in the control field today [8].

Simulink is a graphical simulation tool in Matlab that can be used to centrally model, simulate, and analyze dynamic systems. Simulink provides packaging and modular tools to extend the simulation module library to greatly simplify the design process, reduce design costs, and improve productivity. Simulink includes a range of models and graphical interfaces that users can customize and create suitable modules for their needs. After defining a model, users can simulate and analyze its dynamic characteristics. While the simulation is in progress, the Scope module can also be used to visualize the results of the simulation. Simulink is open and visual, making it more intuitive, convenient and flexible than traditional simulation platforms [9].

Based on the powerful and diverse functions of Matlab and Simulink, this paper uses the principles of circuit analysis to derive the transfer function of the SMU control system and obtain its mathematical model, and select appropriate modules and create graphical interfaces in Simulink to realize the modeling and simulation analysis.

3 CONTROL SYSTEM OF THE SMU

3.1 Structure of Control System

The traditional SMU uses analog hardware to implement the V-I Control module, an internal control circuit using an analog control loop. The circuit of this control method is simple and inexpensive to implement, but it is difficult to provide stable output signals for different devices and meet the test needs of loads. For example, the presence of capacitive loads can easily lead to changes in the phase margin or amplitude margin of the loop gain, which affects the stability of the feedback loop and causes the overshoot, thereby prolonging the signal settling time.

At present, the mainstream SMU structure is a digital control loop, and its simplified diagram is shown in Figure 1 [10]. The idea of the digital control loop is to transfer the V-I Control module inside the processor and configure it through software to optimize the output signal and achieve the ideal response for the load. With the help of fast analog-to-digital converters and the processing power of FPGA, the digital control loop can realize the high-speed stable transformation of the system transfer function, which is completely configured by software to achieve flexible response. It can be seen that the digital control loop is the current development trend of the SMU control system. When researching the performance of the SMU control system, modeling and simulation can facilitate the test of the SMU of different structures, thereby greatly promoting the development and innovation of the SMU in the field of measurement.

3.2 Theoretical Analysis of Control System

Under the premise that the circuit structure is known, the control system usually can be analyzed by analyzing the relationship between the output and input, which needs to divide the subcircuits of different functions into independent modules, and finally obtain the transfer function of each module.

The control system of the SMU is mainly composed of five main parts: PID controller, voltage control circuit, voltage gain stage circuit, output stage circuit and voltage monitor circuit, and the schematic block diagram of the control system is shown in Figure 2.

In a power system, feedback refers to the process of returning the output of the system to the input and changing the input, which in turn affects the function of the system. Feedback can be classified into negative feedback and positive feedback. The former makes the output play the opposite role to the input, so that the error between the system output and the system target is reduced, and the system tends to be stable; The latter makes the output play a similar role to the input, so that the system deviation continues to increase, so that the system oscillates, and the control effect can be amplified [11].

The SMU adopts the feedback regulation in the control system, and uses power amplifiers and other components to form a control circuit to realize the function of inverting amplification of the signal and stabilizing the output signal. The block diagram of the negative feedback loop is shown in Figure 3.

4 MATHEMATICAL MODEL OF THE SMU CONTROL SYSTEM

In the process of theoretical analysis and mathematical model of the SMU, according to the characteristics of the SMU using the amplifier to build the circuit structure and the feedback regulation mechanism to achieve a stable output signal, the steady-state analysis method of the negative feedback circuit, the circuit meets the characteristics of "Virtual Short" and "Virtual Open", is widely utilized [12]. This paper takes HP6633A SMU as an example and follow the method

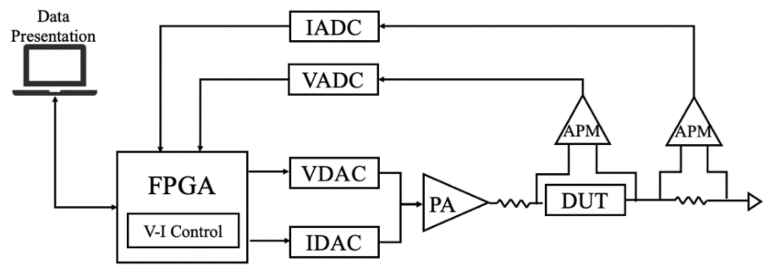

Figure 1: Diagram of a digital control loop system

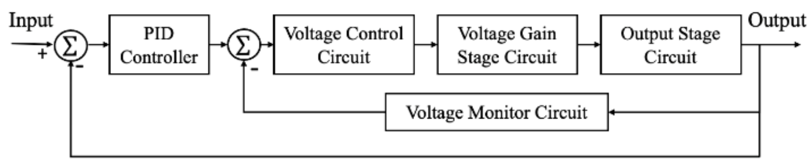

Figure 2: Block diagram of the SMU control system

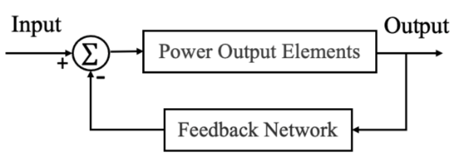

Figure 3: Block diagram of the negative feedback loop

to model the SMU. HP 6633A SMU is the HP-IB system DC power supply, and its circuit can be found in the technical manual, so it is omitted here.

4.1 PID Controller Module

In Eq (2): K_P is proportionality coefficient, K_I is integration coefficient, K_D is differentiation coefficient, and N is filtering coefficient.

$$\frac{y(z)}{x(z)} = K_P + \frac{K_I T}{z-1} + \frac{K_D N}{1 + NT\frac{1}{z-1}} \tag{2}$$

4.2 Voltage Control Circuit Module

In the control system, the voltage control circuit mainly plays the role of stabilizing the voltage to ensure that the voltage will not be overshooting. Figure 4 shows the schematic of the voltage control circuit provided in the technical manual.

The circuit components that play a key role in the circuit are mainly R_{128}, R_{136}, C_{138} and C_{139}. In order to simplify the expression of the transfer function of each module, first define the parallel combination operation expression: prlimp(a,b) = a*b/(a+b).

The transfer function for the voltage control circuit module is:

$$G(s) = prlimp\left(R_{128} + X_{C138}, R_{136} + X_{C139}\right) \tag{3}$$

In Eq (3), X_{Ci} represents the capacitive reactance of the corresponding capacitance.

4.3 Voltage gain stage circuit and output stage circuit module

The voltage gain stage circuit and the output stage circuit are interrelated and inseparable. The SMU signal needs to pass through an output filter circuit before the final output, the schematic of the circuit is shown in Figure 5, and the schematic of the voltage gain circuit and output stage circuit is shown in Figure 6.

The admittance and impedance of the output filter circuit can be expressed by the following equation:

$$\begin{cases} Y_{of} = \frac{1}{R_{224}} + Z_{C101} + \frac{1}{R_{193}+X_{C130}} + \frac{1}{X_{C107}} + \frac{1}{2X_{C108}} \\ Z_{of} = \frac{1}{Y_{of}} \end{cases} \tag{4}$$

In Eq (4), Y_{of} and Z_{of} represent the admittance and impedance of the circuit.

The impedance in the voltage gain stage circuit and output stage circuit is analyzed:

$$\begin{cases} Z_0 = \frac{r_{be101}+(1+hfe_{101})R_{101}}{4} + Z_{of} \\ Z_1 = \frac{r_{be109}+\left(\frac{r_{be109}}{R_{199}}+1+hfe_{101}\right)\left[prlimp(R_{141},X_{L101})+prlimp(Z_0,X_{C125})\right]}{1+\frac{r_{be109}}{R_{199}}} \\ Z_2 = \frac{1}{\frac{1}{R_{114}+X_{C111}}+\frac{1}{X_{C143}}\frac{1}{+X_{C146}}+\frac{1}{R_{113}}} \end{cases} \tag{5}$$

In Eq (5), Z_0 is the impedance of the transistor Q_{101}~Q_{104} and the output filter part circuit, Z_1 is the impedance of the Q_{109} part of the circuit, Z_2 is the impedance of the voltage gain stage, rbe and hfe are the input resistance and current amplification factor of the transistor, and X_{Li} represents the inductive reactance of the corresponding inductance.

After obtaining the Z_0, Z_1, and Z_2, the transfer function of the voltage gain stage circuit can be obtained:

$$G(s) = \frac{prlimp(Z_1, Z_2)\, hfe_{114}}{2\left[r_{be114} + (1 + hfe_{114})\, R_{114}\right]} \tag{6}$$

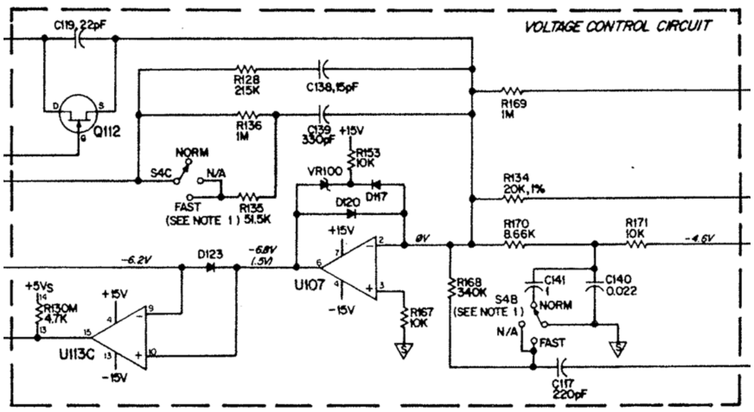

Figure 4: Schematic of the voltage control circuit

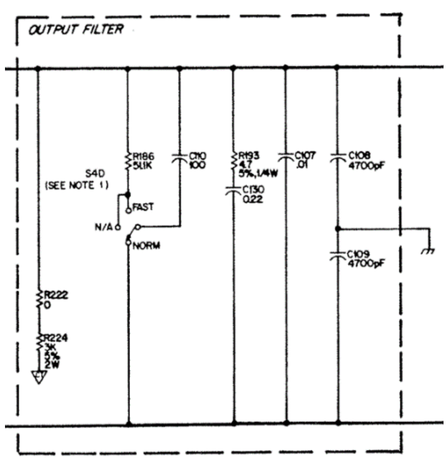

Figure 5: Schematic of the output filter circuit

For the output stage circuit of the SMU, the transfer function expression is:

$$G(s) = \frac{Z_{of}\left(1 + hfe_{101}\right)\left[1 + hfe_{101} + \frac{r_{be109}}{R_{199}}\left(\frac{X_{C125}}{X_{C125}+Z_2}\right)\right]}{r_{be109} + \left(\frac{r_{be109}}{R_{199}} + 1 + hfe_{101}\right)\left[prlimp\left(R_{141}, X_{L101}\right) + prlimp\left(Z_2, X_{C125}\right)\right]} \quad (7)$$

4.4 Voltage Monitor Circuit Module

The presence of the voltage monitor circuit ensures the feedback control function to achieve a stable output voltage. The schematic of this circuit is shown in Figure 7.

There is only one amplifier in the circuit, and the transfer function of the module can be obtained simply by using the steady-state analysis method of the feedback regulation mechanism:

$$G(s) = \frac{R_{165}}{R_{163} + R_{165} + prlimp\left(R_{126}, X_{C106}\right)}\left[\frac{prlimp\left(R_{166}, X_{C162}\right)}{prlimp\left(R_{129}, X_{C155}\right)} + 1\right] \quad (8)$$

5 SIMULATION OF THE SMU CONTROL SYSTEM IN SIMULINK

5.1 Simulation Model

When using Simulink for simulation, we need to write the transfer function of each module in Figure 2 to Simulink's module interface, and then connect each interface to form the model, and finally customize the required input signals and parameters to simulate the control system of the SMU. As can be seen in Figure 8, the simulation system built with Simulink fully adopts the concept of modular design, which is open and portable, and easy to modify the parameters and structure.

5.2 Analysis of transient response and PID controller parameter

The process from the initial state to the final state is called the transient response, and a typical transient response waveform is shown in Figure 9. The delay time td, rising time tr, and peak time tp indicate the speed of the initial stage of the system response. The settling time ts represents the duration of the system transition process, which generally reflects the rapidity of the system. The overshoot reflects the smoothness of the system's response process. The steady-state error reflects the final accuracy of the input signal of the system.

When the SMU powers or measures the device, input disturbances cause changes in the output signal, which is the transient response. Therefore, in order to ensure the stable operation of the SMU, we need to research the control ability of the control system for the transient response. In the presence of input pulse disturbances, the unit impulse response of the SMU is shown in Figure 10. During the simulation, we adjust the PID parameters and select representative simulation curves, as shown in Figures 11 to 13. We will discuss the effect of the PID parameter values on the performance of the transient response during input disturbance in the following paragraphs.

The role of proportion link is proportionally reflecting the deviation of the system. When there is a deviation, it immediately has an adjustment effect to reduce the deviation. Comparing Figures

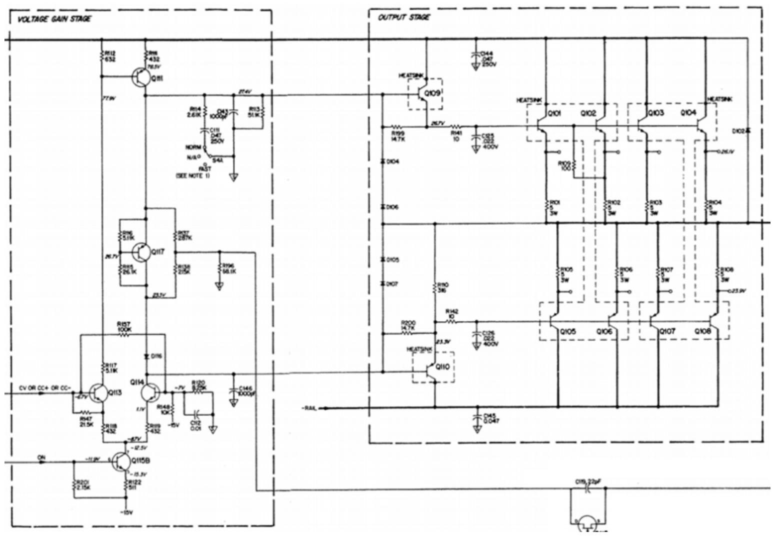

Figure 6: Schematic of the voltage gain stage circuit and output stage circuit

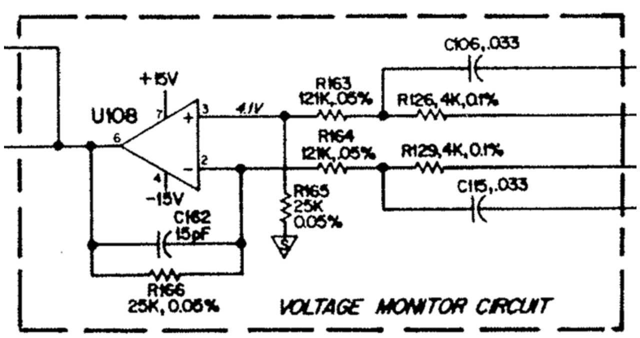

Figure 7: Schematic of the voltage monitor circuit

10 and 11, it can be seen that the larger the K_P, the faster the response speed of the system response, but the greater the degree of overshoot. When the K_P value is too large, the system begins to be unstable and oscillates; However, when the K_P value is small, the response speed is slow, and the settling time is prolonged, which makes the dynamic and static performance of the system worse.

The function of integration link is eliminating the steady-state error. Because when there are steady-state errors in the system, integration link will continue to play a regulating role until there is no difference. Comparing Figure 10 and Figure 12, it can be seen that the larger the K_I, the faster the integration speed, and the greater the overshoot, resulting in its dynamic performance degradation. When the K_I value is too large, the system begins to oscillate. If the K_I is too small, the static difference of the system is difficult to eliminate, resulting in the longer settling time, which affect the adjustment accuracy and dynamic characteristics of the system.

The role of differentiation link is reflecting the change rate of the deviation and predicting the trend of deviation. Therefore, it can produce an advanced control effect. Comparing Figures 10 and 13, it can be seen that the larger the K_D, the smaller the overshoot, and the more stable the regulation system so that the dynamic performance of the system is improved. However, if the K_D becomes large, it may lead to a slow response process, thereby lengthening the settling time, and the anti-interference of the system is also poor. When the K_D value is too large, the system begins to oscillate.

In summary, the performance of the SMU can be improved by the control system. When the SMU is affected by the input disturbance, adjusting the parameter of the PID controller is an effective way to obtain the best transient response with comprehensive performance, so as to meet the requirements of different loads. After building the SMU model in Simulink, adjusting parameters can be applied to observe the dynamic and static characteristics of the system. This method is simple to operate, and the waveform of the simulation result is accurate and intuitive.

6 CONCLUSION

In view of the high cost and difficulty of entity optimization, this paper proposes to build a mathematical model of the SMU in Simulink and simulate the functions of the control system to reduce the difficulty and cost of the improvement scheme. The simulation results show that the PID controller can optimize the performance of the SMU transient response under the input disturbance. Designing and improving the SMU on the basis of Simulink model is an economical, convenient and intuitive to research its static and dynamic characteristics, which can provide reference for the design and improvement of the SMU and make the SMU better serve the field of electrical testing.

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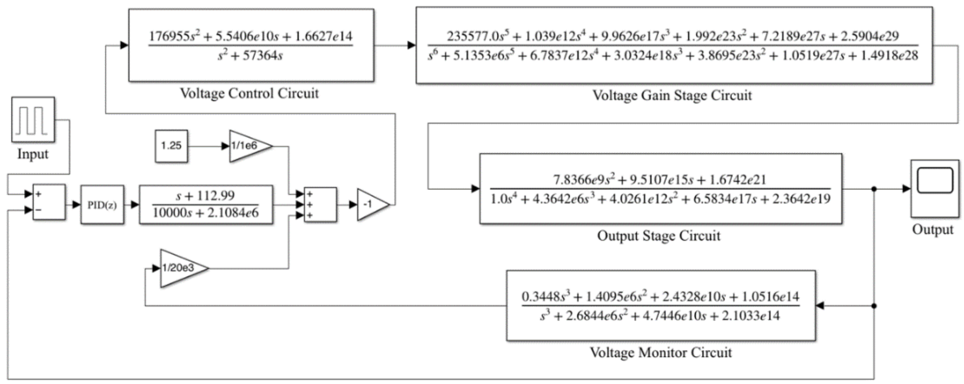

Figure 8: Model of the SMU control system in Simulink

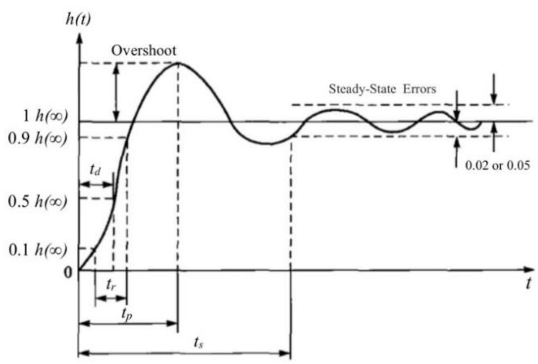

Figure 9: A typical transient response waveform

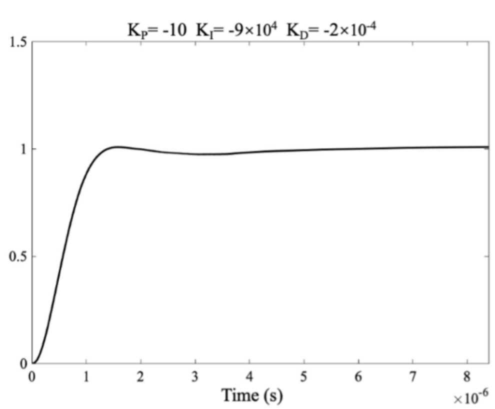

Figure 10: Transient response under impulse disturbance

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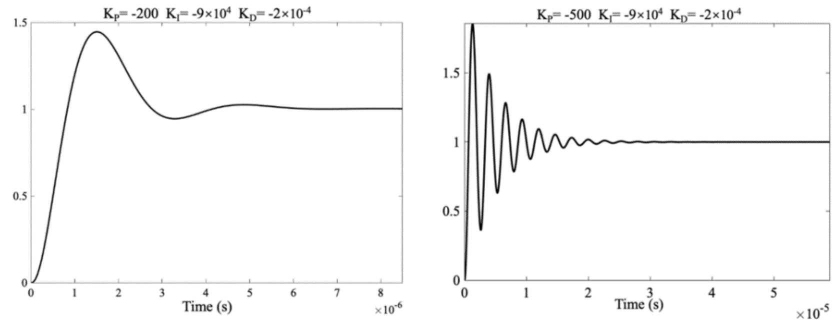

Figure 11: Comparison of transient response under impulse disturbance 1

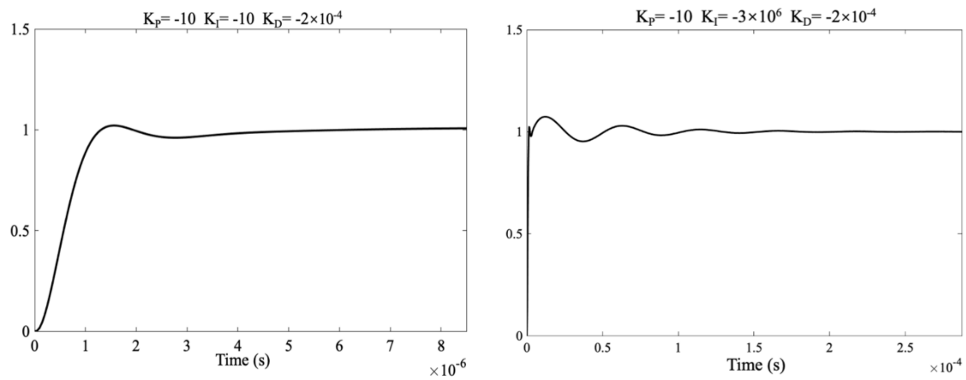

Figure 12: Comparison of transient response under impulse disturbance 2

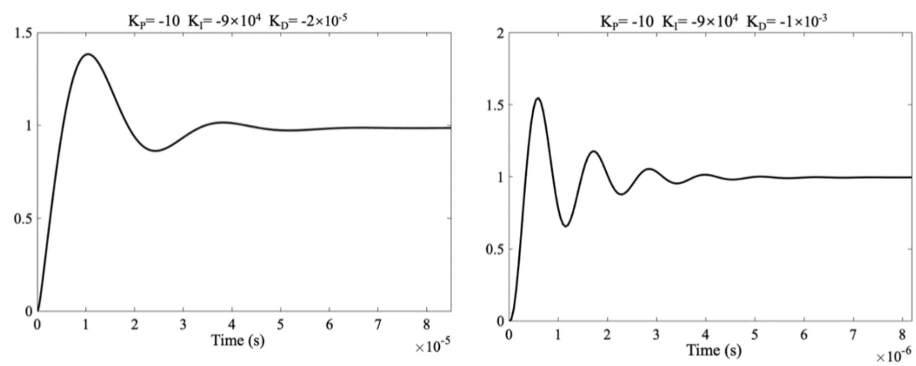

Figure 13: Comparison of transient response under impulse disturbance 3