Experiment No: 01

Experiment Name: Introduction to Simulink.

Objectives:
The purpose of this experiment is to:
1. Know about the background information and introduction of Matlab/Simulink.
2. Build a second order system model from the transfer function and simulate the step response in Simulink platform.
3. Explore other build-in functions in Simulink.
4. Observe the step response and characteristics of the second order system.

Theory:
Simulink is a tool for simulating dynamic systems with a graphical interface specially developed for this purpose. Within the Matlab environment, Simulink is a Matlab toolbox that differs from the other toolboxes, both in this special interface and in the special "programming technique" associated with it. Simulink is an extension to Matlab. In Simulink, block diagram models of dynamic systems build instead of text code. It is easy to model complex nonlinear systems. Simulink can model both continuous and discrete-time components. A second order system is simulated here from its transfer function to observe the step response of the system. A Transfer Function is a mathematical representation of a system and is simply the ratio of the system input to the system output.

Required Software: Matlab/Simulink

Experimental Analysis:

i) Example of an underdamped second order system:

Transfer Function, G(s) = $\frac{9}{s^2 + 2s + 9}$

- **Implementation Diagram:**

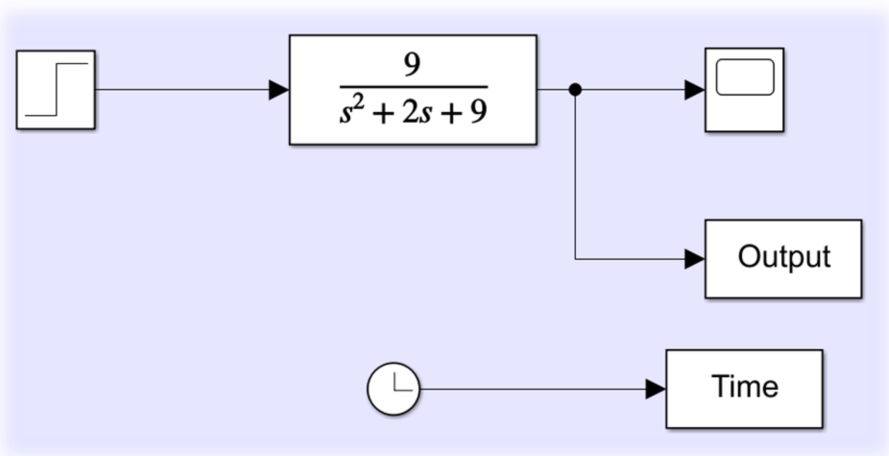

Figure 1.1: Implementation Diagram in Simulink

- **Result:**

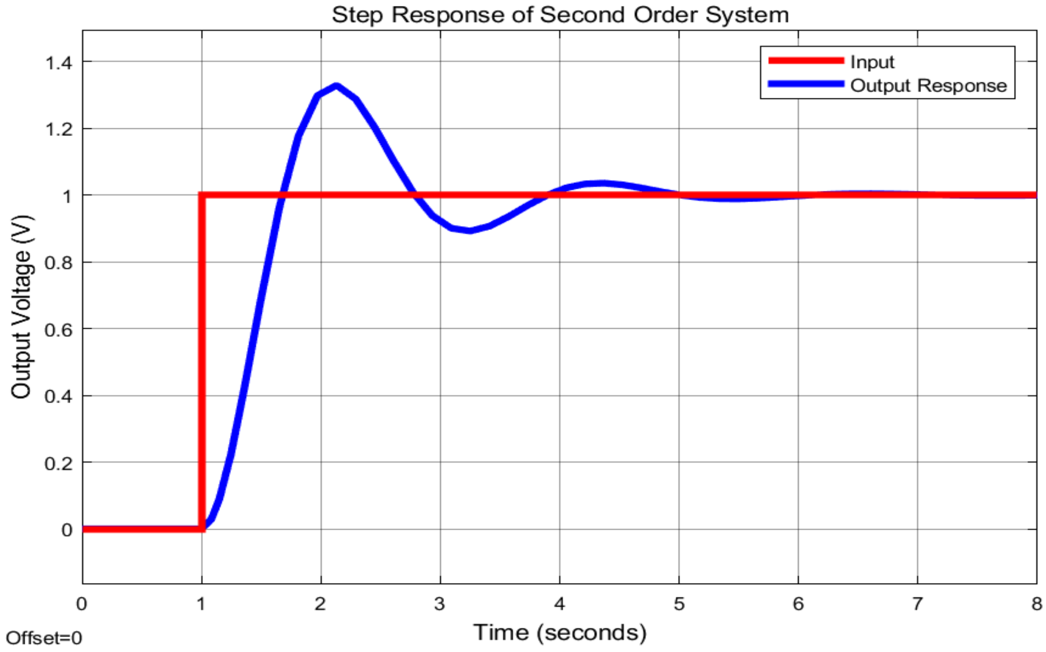

Figure 1.2: Input & Output Response of the Second Order System

Figure 1.2 represents the input and output response of a second order system. Input signal is a step signal varied at time duration 0 to 8 sec. Theoretically, compare the numerator and denominator of the given transfer function with the general 2nd order transfer function, $\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$;

Un-damped natural frequency, ω_n = 3 & Damping ratio, $\zeta = \frac{1}{3}$. So, the system is an underdamped system ($0 < \zeta < 1$). The unit step response of the second order system is showing damped oscillations (decreasing amplitude).

ii) Example of an overdamped second order system:

Transfer Function, G(s) = $\frac{9}{s^2 + 9s+9}$

- **Implementation Diagram:**

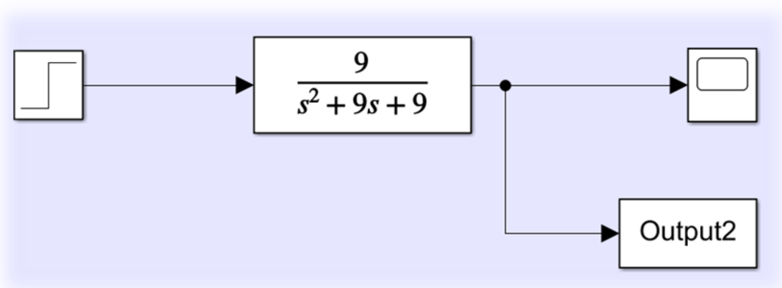

Figure 1.3: Implementation Diagram in Simulink

- **Result:**

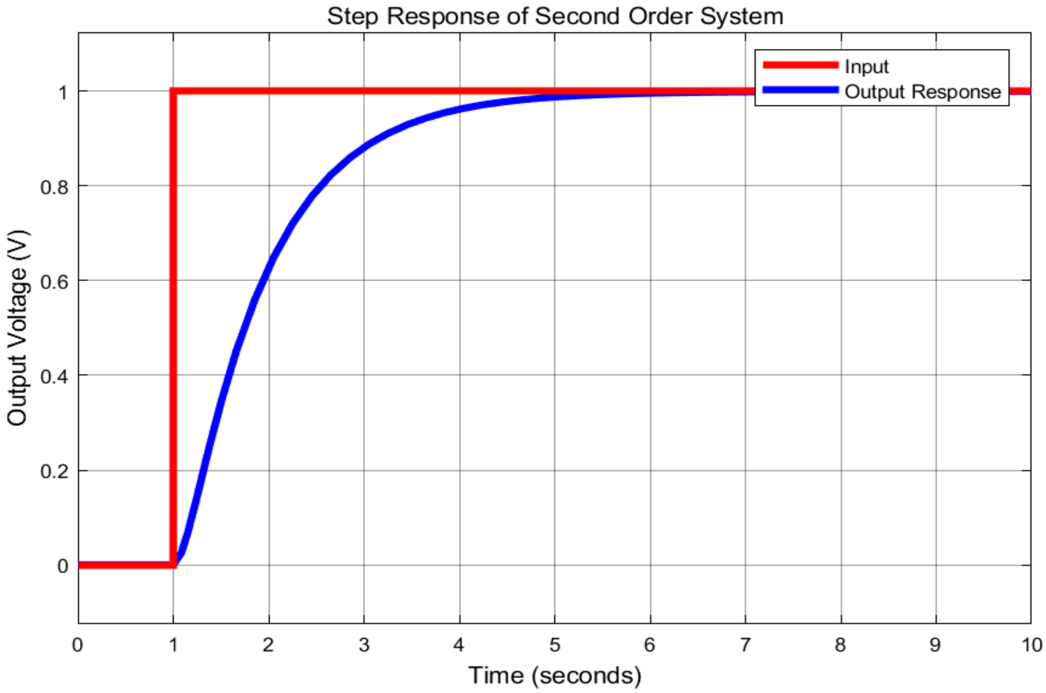

Figure 1.4: Input & Output Response of the Second Order System

Figure 1.4 represents the input and output response of a second order system. Input signal is a step signal varied at time duration 0 to 10 sec. Theoretically, compare the numerator and denominator of the given transfer function with the general 2nd order transfer function, $\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$; Un-damped natural frequency, ω_n = 3 & Damping ratio, $\zeta = \frac{3}{2}$ = 1.5. So, the system is an overdamped system (ζ > 1).

iii) Example of an undamped second order system:

Transfer Function, G(s) = $\frac{9}{s^2+9}$

- **Implementation Diagram:**

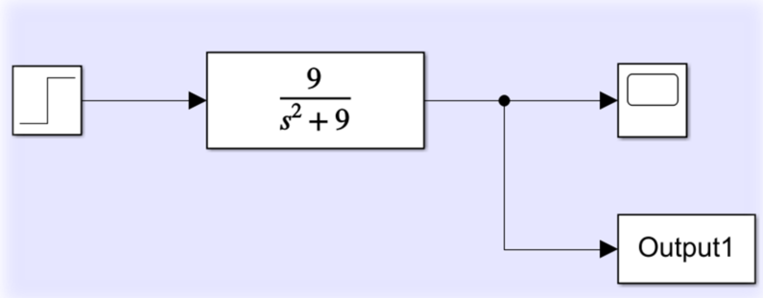

Figure 1.5: Implementation Diagram in Simulink

- **Result:**

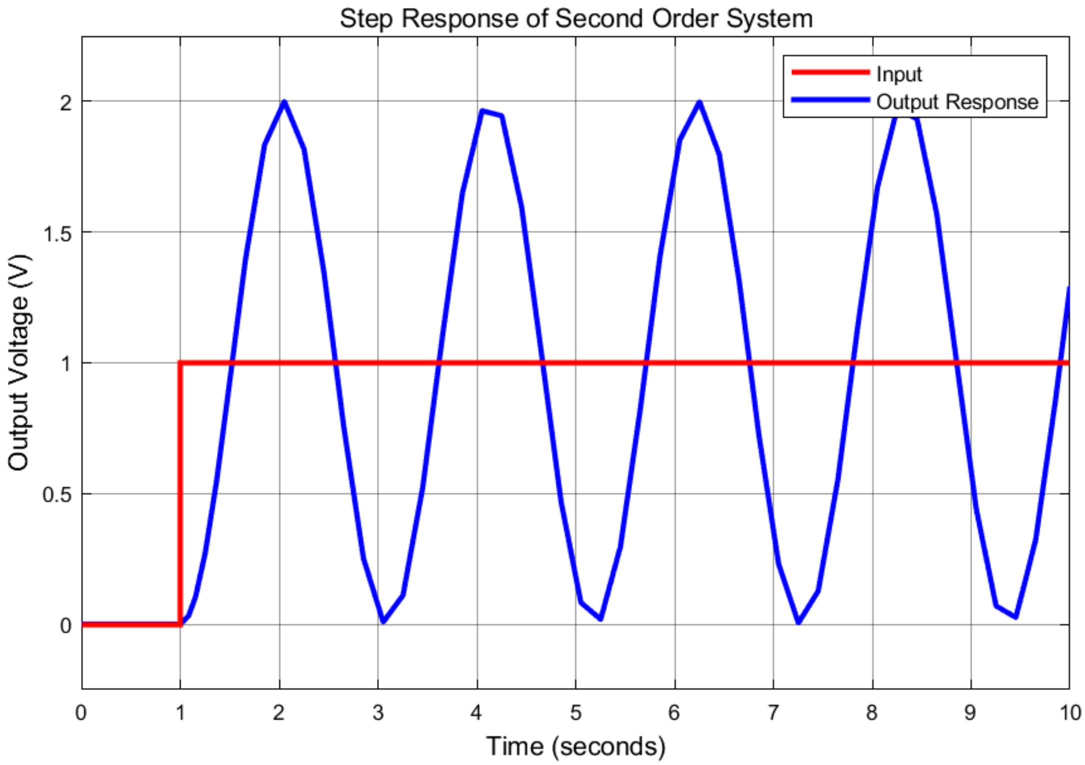

Figure 1.6: Input & Output Response of the Second Order System

Figure 1.6 represents the input and output response of a second order system. Input signal is a step signal varied at time duration 0 to 10 sec. Theoretically, compare the numerator and denominator of the given transfer function with the general 2nd order transfer function, $\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$;

Un-damped natural frequency, ω_n = 3 & Damping ratio, $\zeta = 0$. So, the system is an undamped system (ζ=0). The output response is showing no exponential curve, only have continuous periodic time signal with constant amplitude and frequency.

Discussion: In this experiment, a second order system model was built from the transfer function and step response is observed in Simulink platform. The main purposes of this experiment were acquired the knowledge about the background information and introduction of Matlab/Simulink and exploring the build-in functions in Simulink. The ability is acquired to draw the block diagram and to implement the system on Simulink platform from its transfer function. According the value of ζ, a second-order system can be set into one of the four categories: i) Overdamped, when ζ >1; ii) Underdamped, when 0 < ζ < 1; iii) Undamped, when ζ=0; iv) Critically damped, when ζ=1. The input & output response for the second order system was observed and determined the nature of the system. Thus, the experiment was successfully done.

Experiment No: 02(a)

Experiment Name: Speed Control of an Armature Voltage Controlled DC Motor in the MATLAB Simulink Platform.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the operations and characteristics of armature-controlled DC motor.
2. Design an armature voltage-controlled DC motor from its circuit equations to control the speed.
3. Observe the effect of parameters changes on the output of the DC motor Converters using MATLAB Simulink.
4. Observe the output response using PID Controller.

Theory:
The circuit diagram of a DC motor is shown in the following figure. From this figure, the circuit equations can be written as follows:

$$I_a(s) = \frac{1}{(R_a+sL_a)}\left(E_b(s) - V_{in}(s)\right) \tag{1a}$$

$$T_m(s) = k_t I_a(s) \tag{2a}$$

$$\omega(s) = \frac{T_m(s)}{Js+f} \tag{3a}$$

$$E_b(s) = k_b(s)\,\omega(s) \tag{4a}$$

$$\theta(s) = \frac{1}{s}\omega(s) \tag{5a}$$

Circuit Diagram:

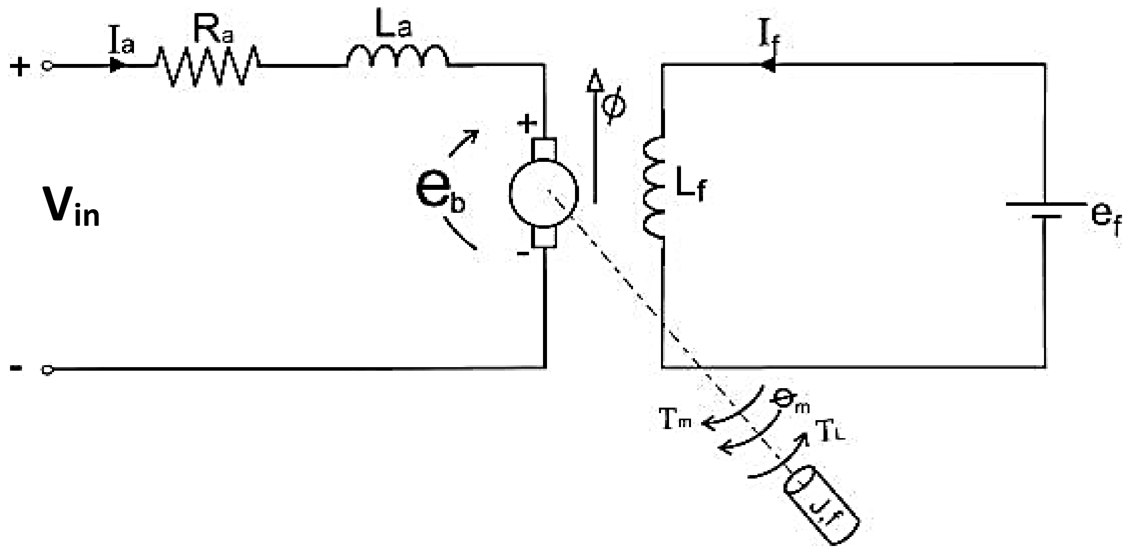

Figure 2.1: Circuit Diagram of a DC motor

Using equations (1a) -(5a), the block diagram can be obtained as follows:

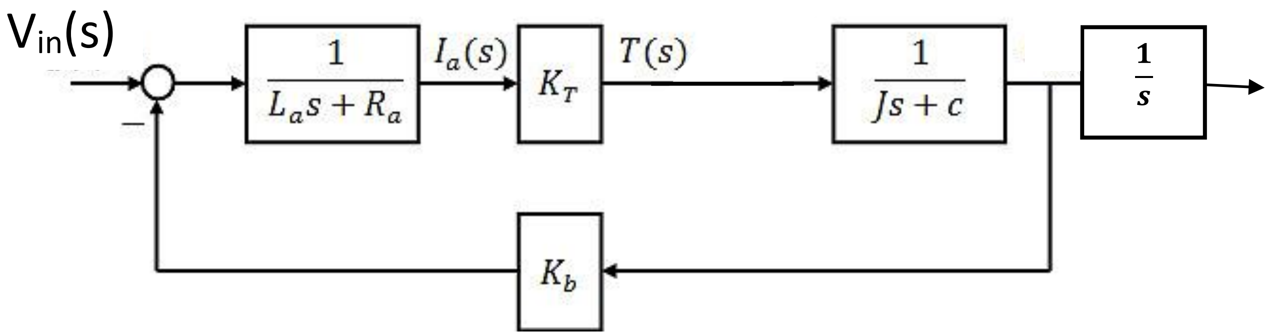

Figure 2.2: Block Diagram

Required Software: MATLAB/Simulink

Experimental Analysis:

iv) Speed Control of an Armature Voltage Controlled DC Motor for Different Proportional Gain:

- **Implementation Diagram:**

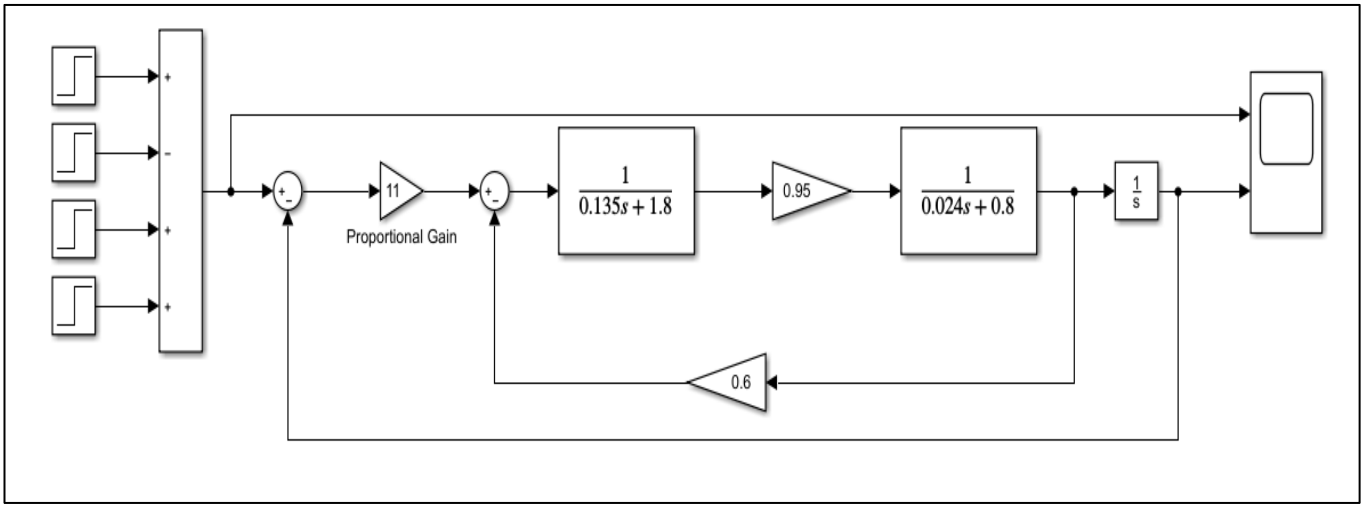

Figure 2.3: Implementation Diagram in Simulink

- **Result:**

Figure 2.4 represents the input and output response for speed control of an armature voltage-controlled DC motor. Input signal is a step signal varied at time duration 0 to 7 sec and output response is observed for different value of proportional gain (such as – 20, 11 & 30). Gain 20 & 30 is showing over-showed and gain 11 is showing under-showed. There are different values of delay time, rise time, peak time and setting time is drawn here for different gain values.

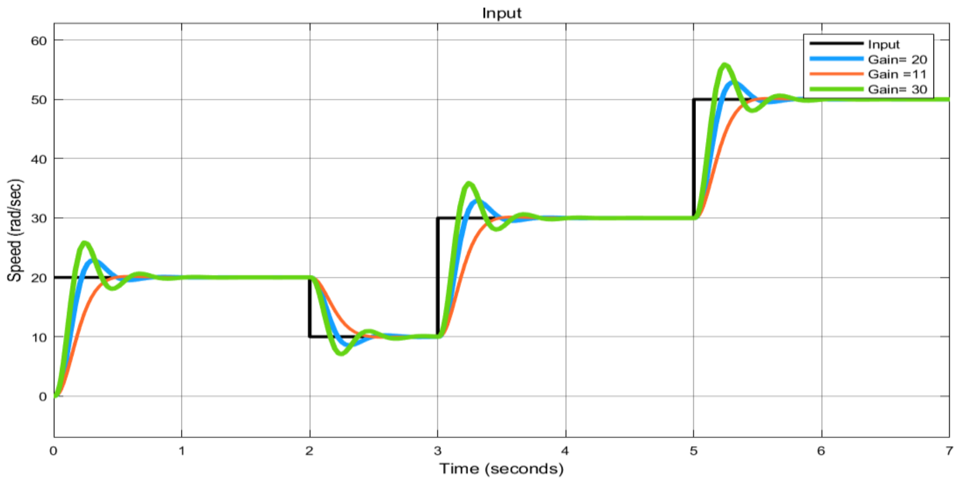

Figure 2.4: Input & Output Response of the System

v) **Speed Control of an Armature Voltage Controlled DC Motor Using PI Controller**

➢ **Implementation Diagram:**

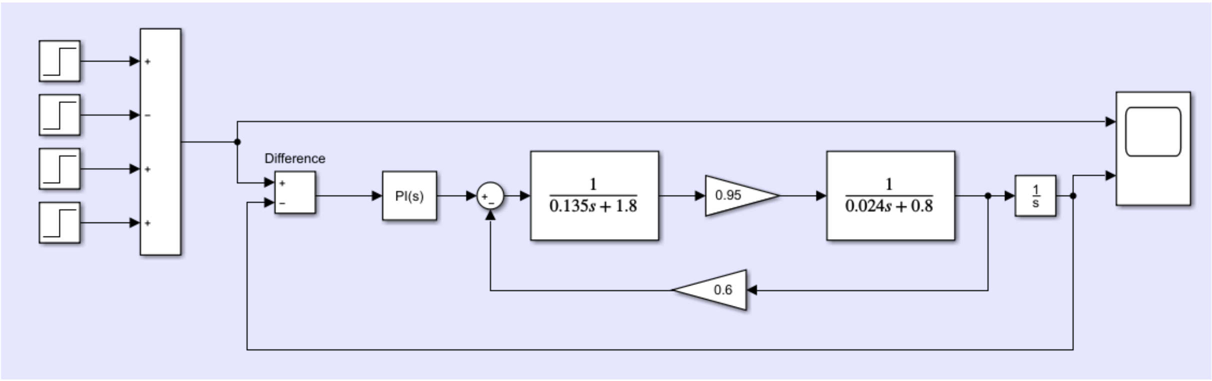

Figure 2.5: Implementation diagram of the system

Result:

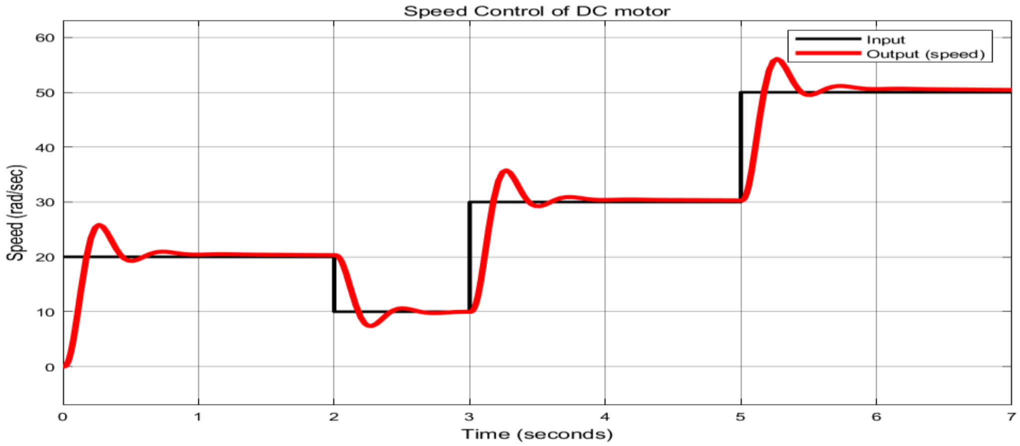

Figure 2.6: Input & Output Response

Figure 2.6 represents the input and output response for speed control of an armature voltage-controlled DC motor. Input signal is a step signal varied at time duration 0 to 7 sec and output response is observed by controlling with PI controller. A PI controller is used here to generate next input by comparing with the output and the signal at every instant of time.

vi) **Speed Control of an Armature Voltage Controlled DC Motor Using PID Controller**

➢ **Implementation Diagram:**

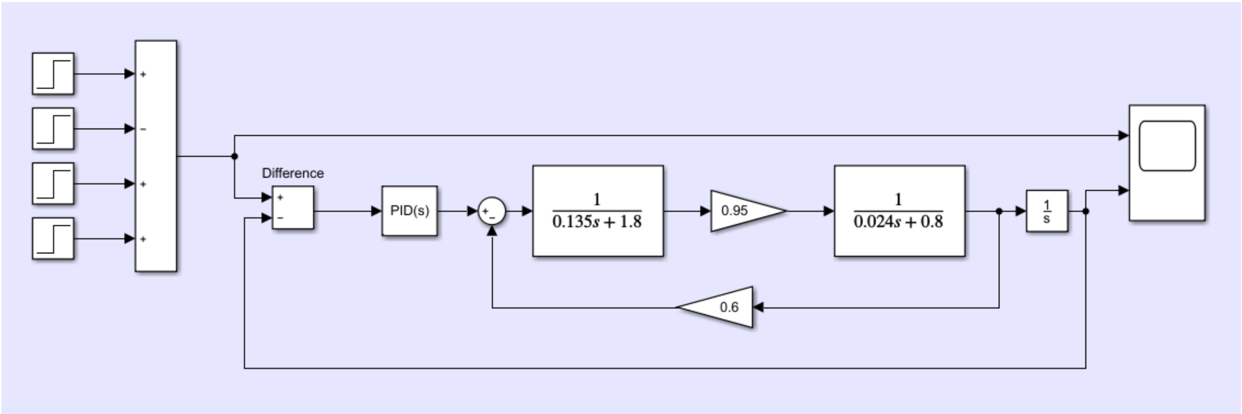

Figure 2.7: Implementation Diagram of the system

➢ **Result:**

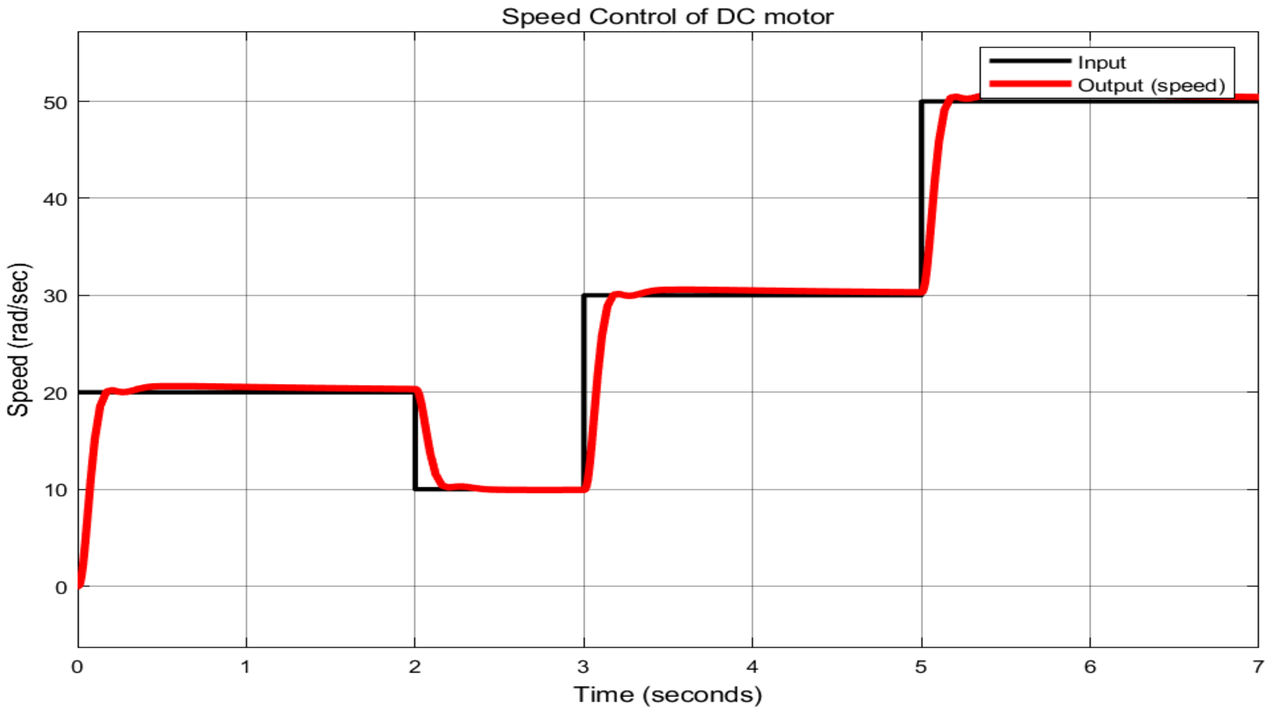

Figure 2.8: Input & Output Response

Figure 2.8 represents the input and output response for speed control of an armature voltage-controlled DC motor. Input signal is a step signal varied at time duration 0 to 7 sec and output response is observed by controlling with PID controller. A PID controller is used here to generate next input by comparing with the output and the signal at every instant of time. PID controller's output is improved from previous PI controller's output.

Discussion: This experiment was about the operations and characteristics of an armature voltage-controlled DC motor to control its speed. The ability is acquired to draw the block diagram and to implement the system on Simulink platform. The input & output response for a DC motor for different proportional gain value was observed. Finally, the speed of motor was controlled by using a build-in PID controller. Everybody should have to select the appropriate values of PID controllers' parameter (P, I & D) to get best performance. Thus, the experiment was successfully done.

Experiment No: 02(b)

Experiment Name: Speed Control of a Field Controlled DC Motor in the MATLAB Simulink Platform.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the operations and characteristics of field-controlled DC motor.
2. Design a field-controlled DC motor from its circuit equations to control the speed of motor.
3. Observe the effect of parameters changes on the output of the DC motor Converters using MATLAB Simulink.
4. Observe the output response using PID Controller.

Theory: The circuit diagram of a DC motor is shown in the following figure. From this figure, the circuit equations can be written as follows:

$$I_f(s) = \frac{V_f(s)}{(R_f+sL_s)} \tag{1b}$$

$$T_m(s) = k_t I_f(s) \tag{2b}$$

$$\omega(s) = \frac{T_m(s)}{Js+f} \tag{3b}$$

$$\theta(s) = \frac{1}{s}\omega(s) \tag{4b}$$

Circuit Diagram:

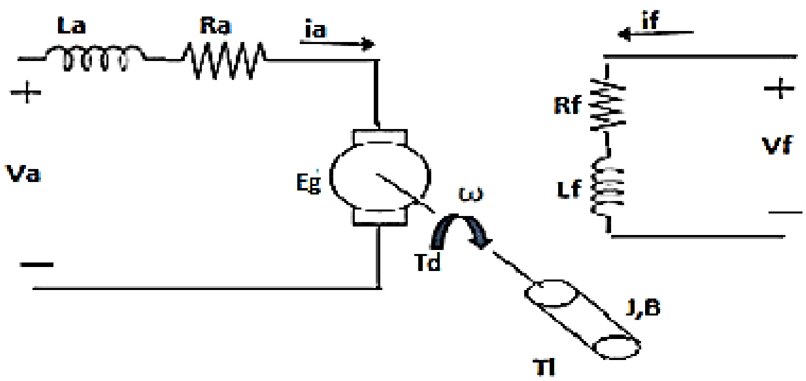

Figure 2.9: Circuit Diagram of a DC motor

Using equations (1b) -(4b), the block diagram can be obtained as follows:

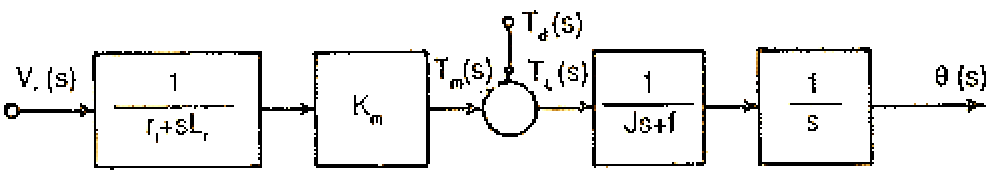

Figure 2.10: Block Diagram

Required Software: MATLAB/Simulink

Experimental Analysis:

i) Speed Control of Field Controlled DC Motor for Different Proportional Gain:

➢ **Implementation Diagram:**

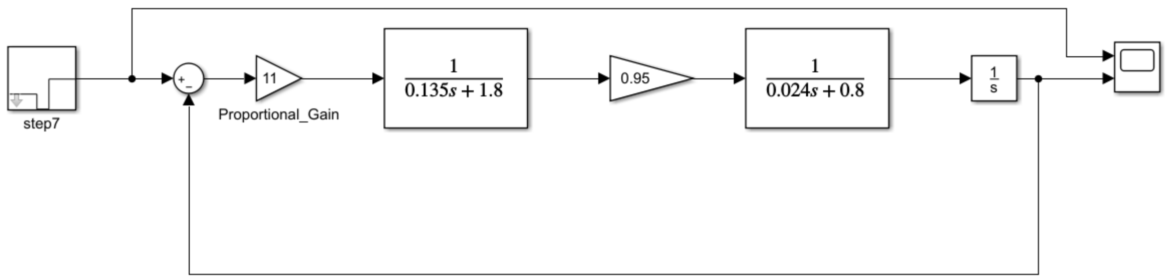

Figure 2.11: Implementation Diagram in Simulink

➢ **Result:**

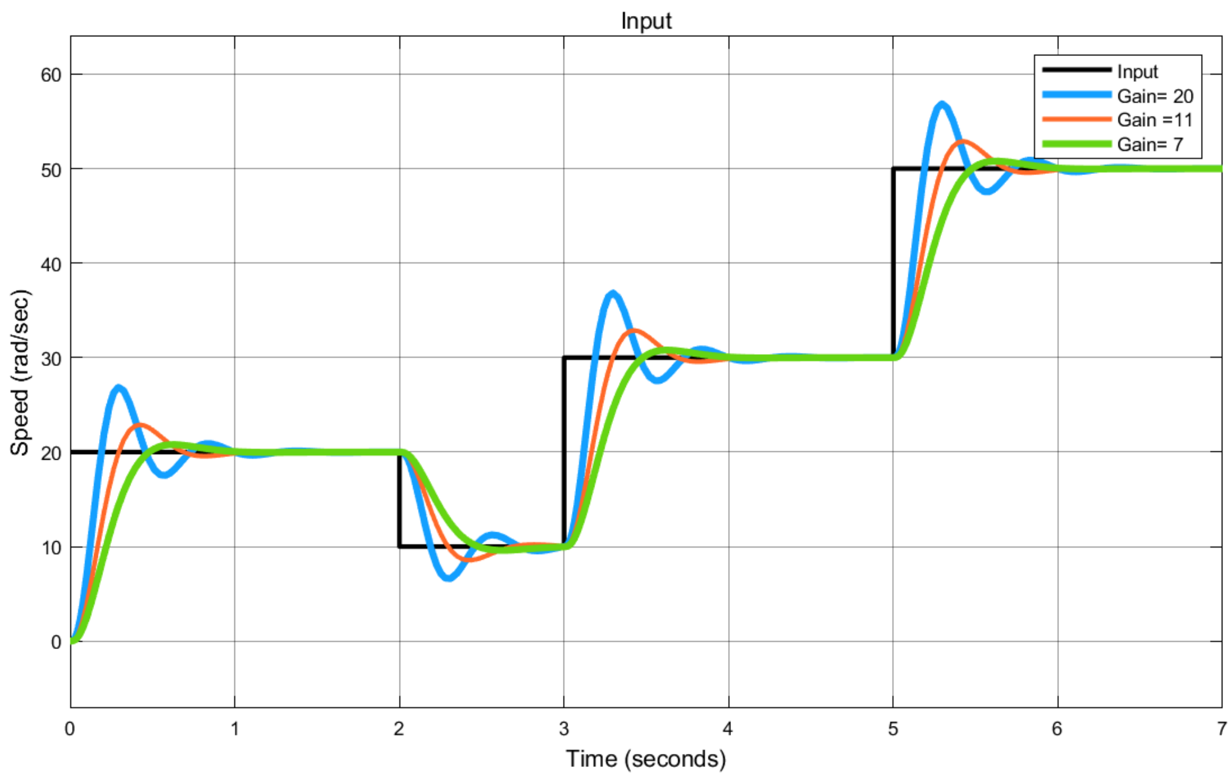

Figure 2.12: Input & Output Response of the System

Figure 2.12 represents the input and output response for speed control of a field-controlled DC motor. Input signal is a step signal varied at time duration 0 to 7 sec and output response is observed for different value of proportional gain (such as – 20, 11 & 7). Gain 20 & 11 is showing over-showed and gain 7 is showing under-showed. There are different values of delay time, rise time, peak time and setting time is drawn here for different gain values.

ii) Speed Control of a Field Controlled DC Motor Using PID Controller

➢ **Implementation Diagram:**

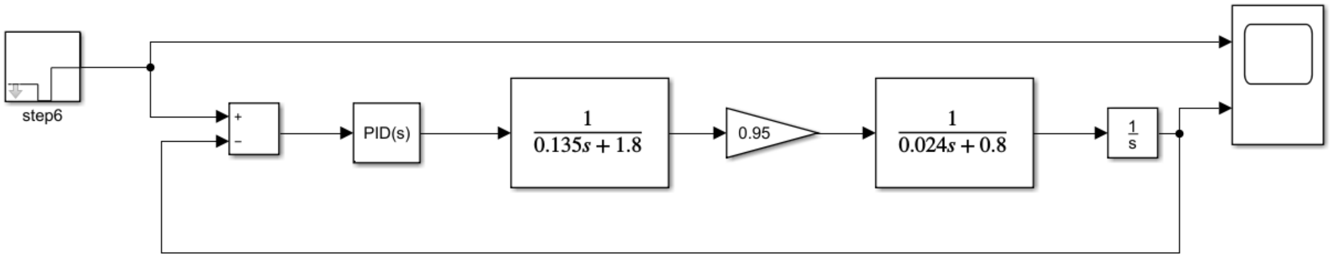

Figure 2.13: Implementation Diagram of the system

➢ **Result:**

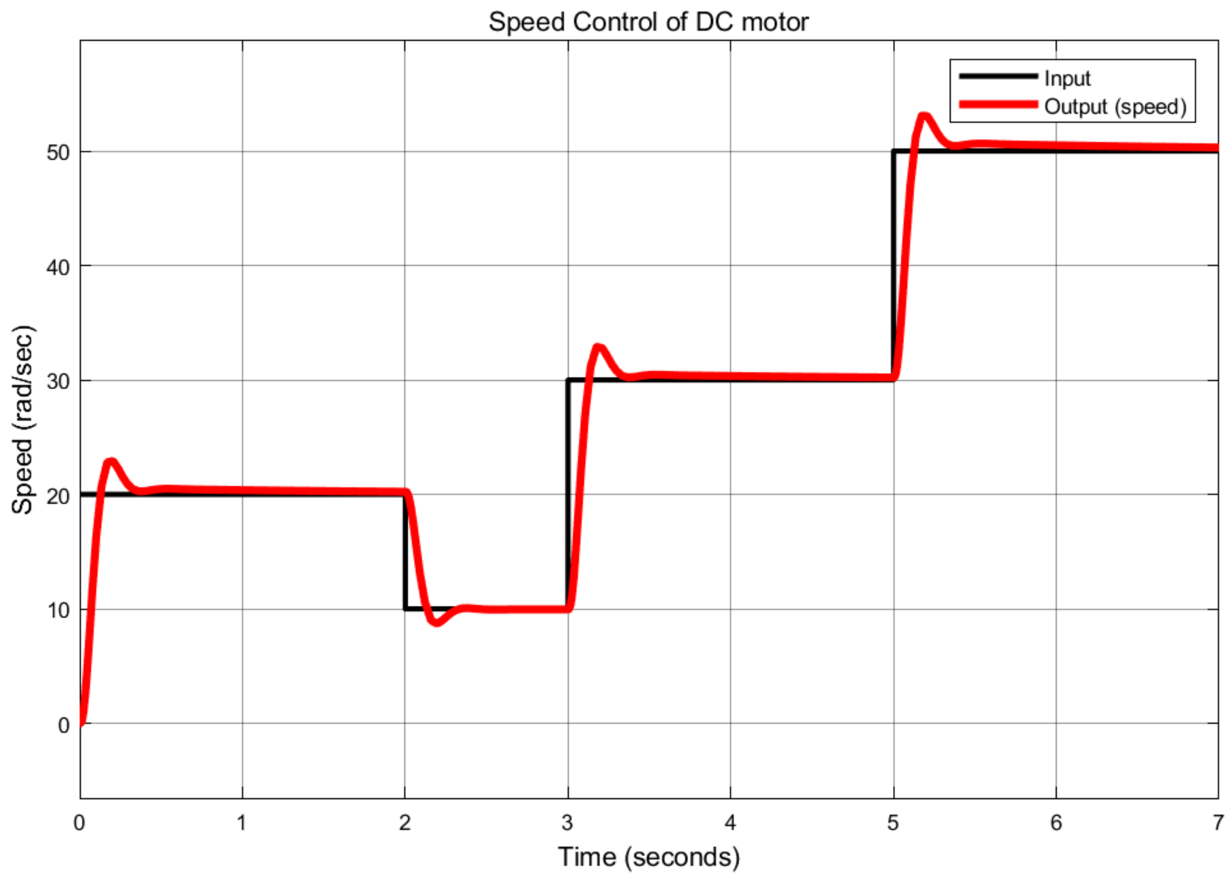

Figure 2.14: Input & Output Response

Figure 2.14 represents the input and output response for speed control of a field-controlled DC motor. Input signal is a step signal varied at time duration 0 to 7 sec and output response is observed by controlling with PID controller. A PID controller is used here to generate next input by comparing with the output and the signal at every instant of time. PID controller's output is improved from previous one.

<u>Discussion</u>: This experiment was about the operations and characteristics of a field-controlled DC motor to control its speed. The ability is acquired to draw the block diagram and to implement the system on Simulink platform. The input & output response for a DC motor for different proportional gain value was observed. Finally, the speed of motor was controlled by using a build-in PID controller. Everybody should have to select the appropriate values of PID controllers' parameter (P, I & D) to get best performance. Thus, the experiment was successfully done.

Experiment No: 03 (a)

Experiment Name: Study the Characteristics of Time Response of First Order Control System.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the characteristics of time response of first order control system.
2. Design a 1st order control system from its transfer function.
3. Observe the effect of parameters changes on the output response of the 1st order control system using MATLAB Simulink.
4. Observe the output response for different input signal (such as- unit step, unit impulse & ramp).

Theory:
The transfer function of a first order system can be expressed as follows:

$$\frac{C(s)}{R(s)} = \frac{K}{sT + 1}$$

which can be rewritten as follows:

$$C(s) = R(s)\frac{K}{sT + 1}$$

where K is the D.C gain and T is the time constant of the system.

- Time constant is a measure of how quickly a 1st order system responds to a unit step input.
- D.C Gain of the system is a ratio between the input signal and the steady state value of the output.

Block Diagram:

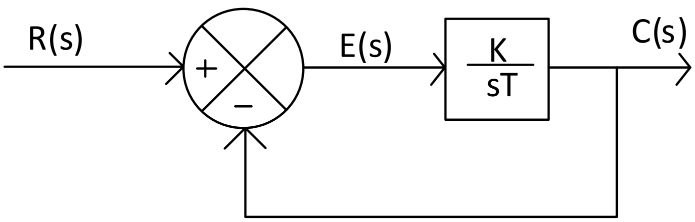

Figure 3.1: Block Diagram

Required Software: MATLAB/Simulink

Experimental Analysis:

- **Applying a unit step signal as input and the time constant T = 2 second and the values of D.C gain, K = 0.5, 2, 5 & 20 to get the output response c(t) of the 1st order system:**

i) Implementation Diagram:

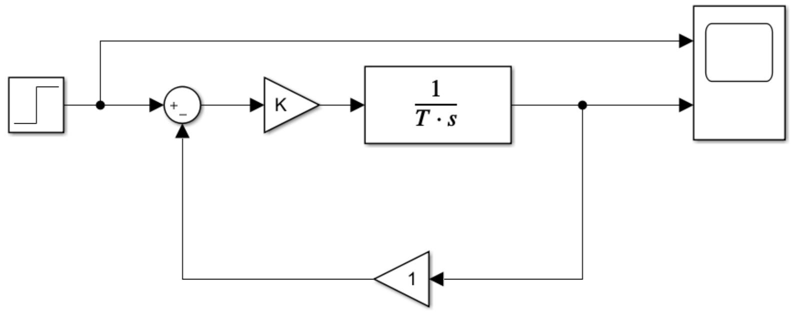

Figure 3.2: Implementation Diagram in Simulink

ii) Result:

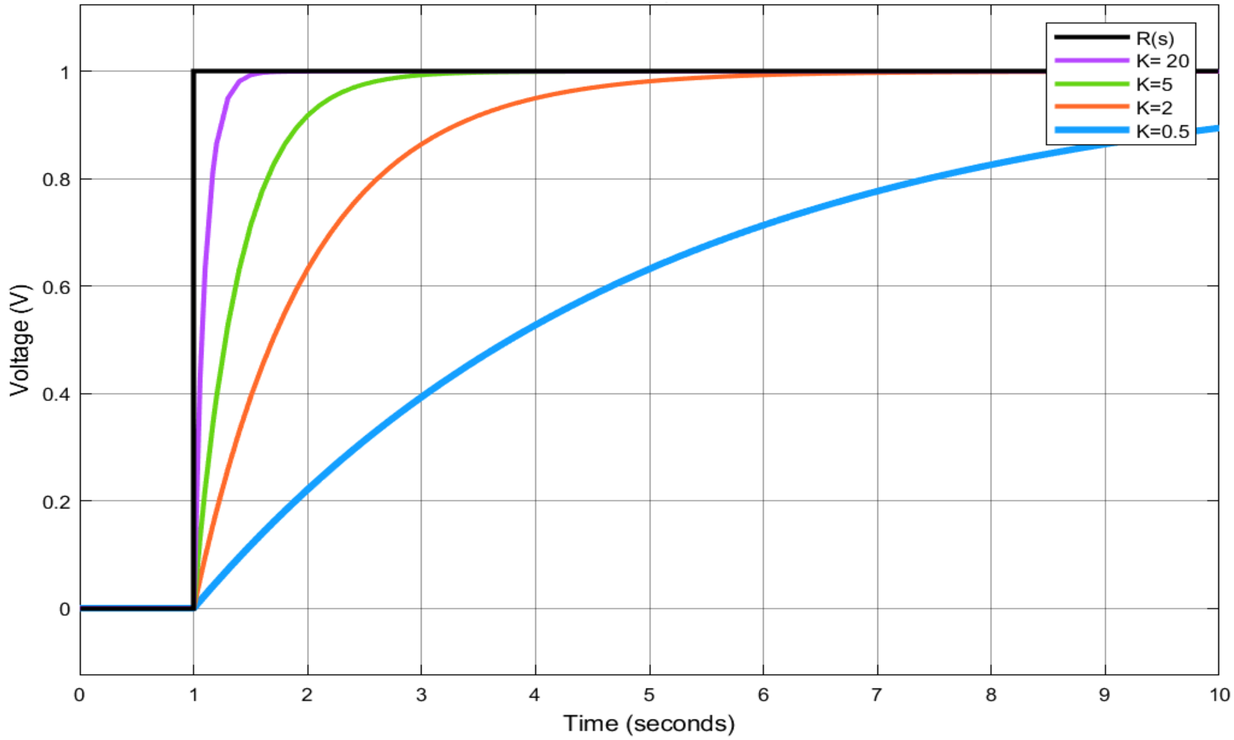

Figure 3.3: Input & Output Response

Figure 3.3 represents the input and output response for the 1st order control system. Input signal, R(s) is a unit step signal with time duration 0 to 10 sec and output response is observed for different value of D.C. gain (such as – 20, 5, 2 & 0.5). For DC gain 20, it is showing lowest setting time and DC gain 0.5 is showing largest response time. Setting time is decreased by increasing the DC gain.

- **Applying a ramp signal as input and the time constant T = 2 second and the values of D.C gain, K = 0.5, 2, 5 & 20 to get the output response c(t) of the 1st order system:**

i) Implementation Diagram:

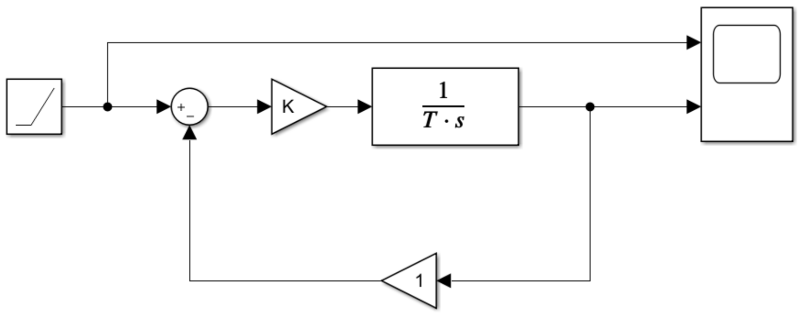

Figure 3.4: Implementation diagram of the system

ii) Result:

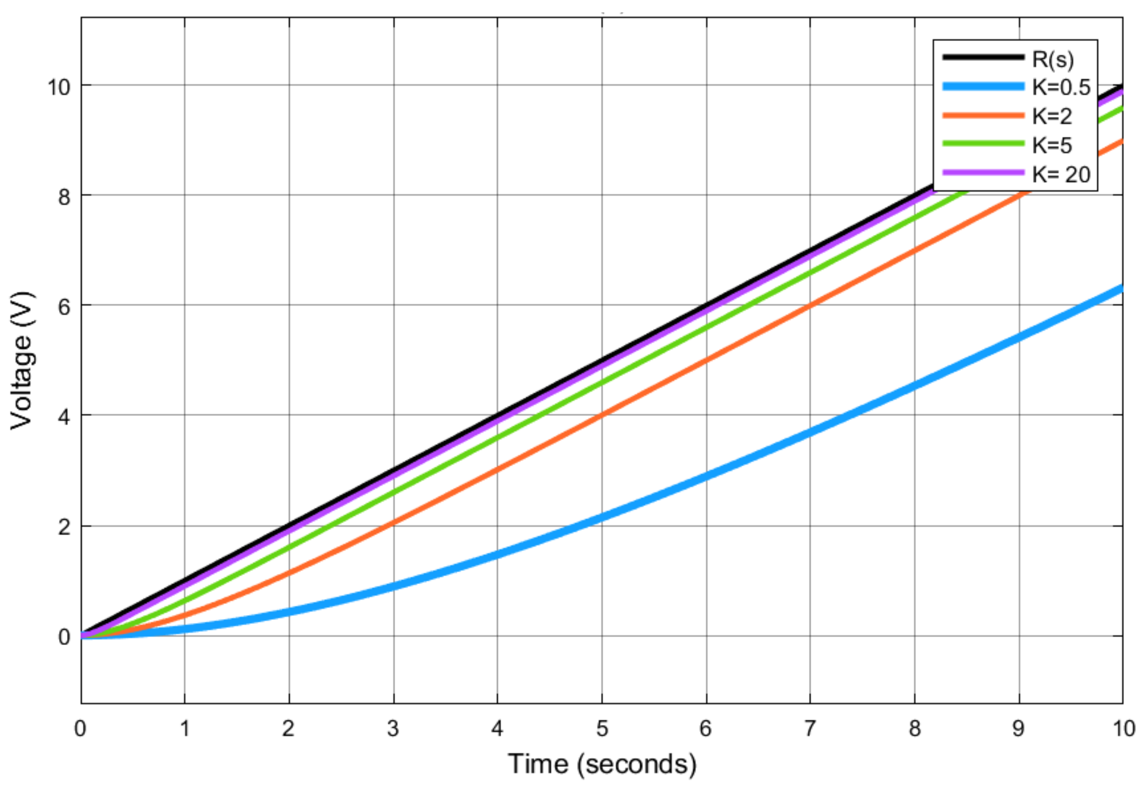

Figure 3.5: Input & Output Response

Figure 3.5 represents the input and output response for the 1st order control system. Input signal, R(s) is a ramp signal with time duration 0 to 10 sec and output response is observed for different value of D.C. gain (such as – 20, 5, 2 & 0.5). The output response, c(t) follows the unit ramp input signal for all positive values of t, but there is a deviation from the input signal.

➢ **Applying an impulse signal as an input and the time constant T = 2 second and the values of D.C gain, K = 0.5, 2, 5, 20 to get the output response c(t) of the 1st order system:**

i) Implementation Diagram:

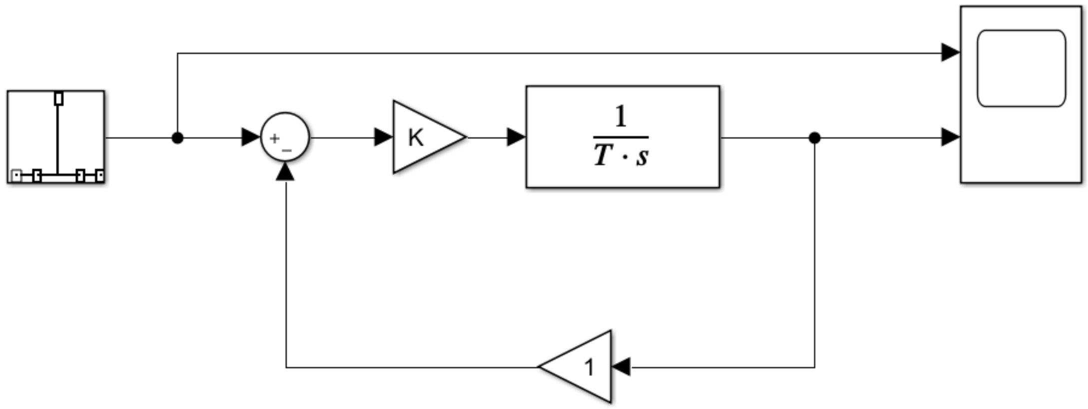

Figure 3.6: Implementation Diagram of the system

ii) Result:

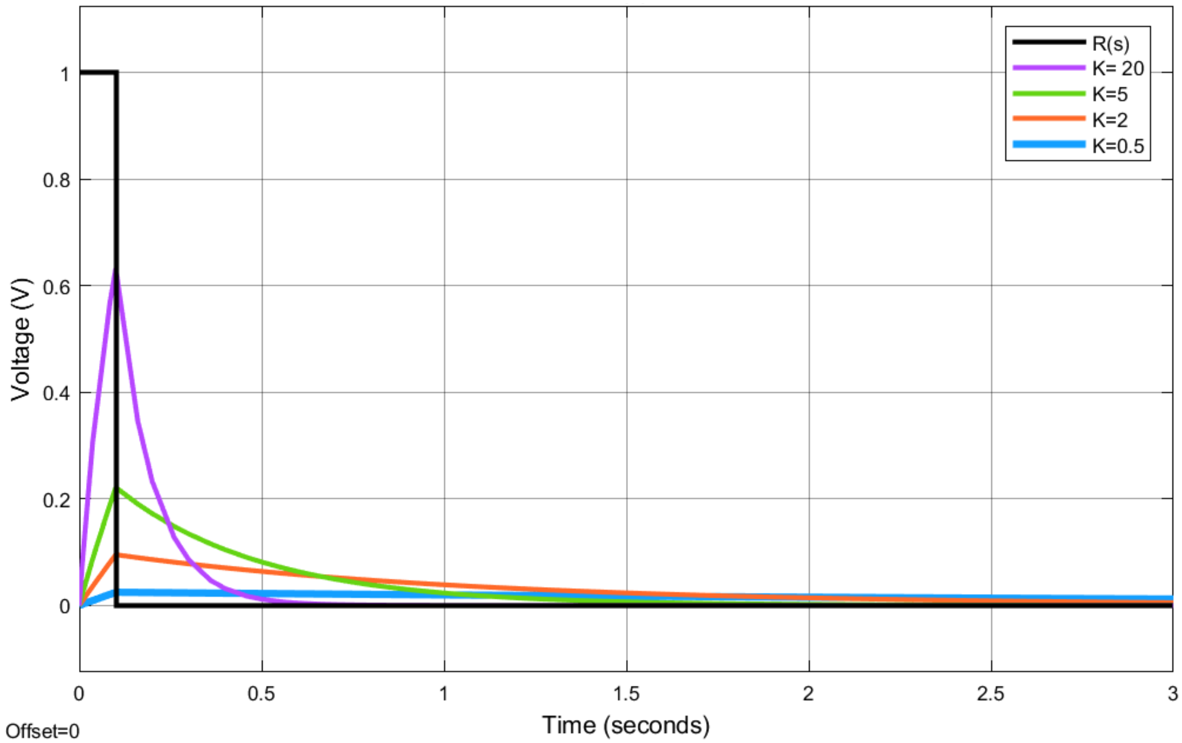

Figure 3.7: Input & Output Response

Figure 3.7 represents the input and output response for the 1st order control system. Input signal, R(s) is an impulse signal with time duration 0 to 3 sec and output response is observed for different value of D.C. gain (such as – 20, 5, 2 & 0.5). It is not possible to describe the effect of D.C gain, since impulse response is not convenient for 1st order control system.

Discussion: This experiment was about the characteristics of time response of first order control system. The ability is acquired to draw the block diagram and to implement the first order system on Simulink platform from its transfer function. The effect of parameters changes on the output response of the control system was observed. Basically, the D.C gain, K is varied to observe the output response of the system. Also, the output response for different input signal (such as- unit step, unit impulse & ramp) for the system was observed. Thus, the experiment was successfully done.

Experiment No: 03 (b)

Experiment Name: Study the Characteristics of Time Response of Second Order Control System.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the characteristics of time response of second order control system.
2. Design a 2nd order control system from its transfer function.
3. Observe the effect of parameters changes on the output response of the 2nd order control system using MATLAB Simulink.
4. Observe the output response for different input signal (such as- unit step, unit impulse & ramp).

Theory: A general second-order system is characterized by the following transfer function:

$$\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Where ω_n is the undamped natural frequency of the second order system, which is the frequency of oscillation of the system without damping and ζ is the damping ratio which is a measure of the degree of resistance to change in the system output.

Block Diagram:

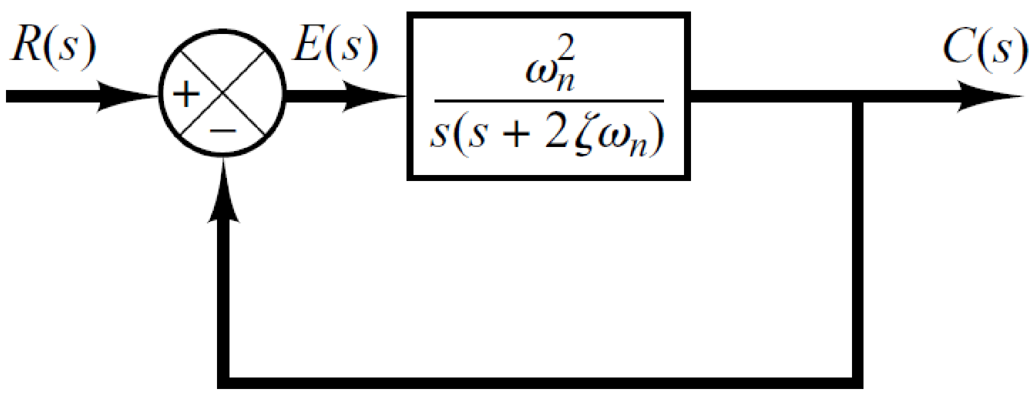

Figure 3.8: Block Diagram

Required Software: MATLAB/Simulink

Experimental Analysis:

- **Applying a unit step signal as input, the undamped natural frequency, $\omega_n = 2\ rad/sec$ and the values of damping ratio, ζ = 0.5, 0, 1 & 3 to get the output response c(t) of the 2nd order system:**

i) Implementation Diagram:

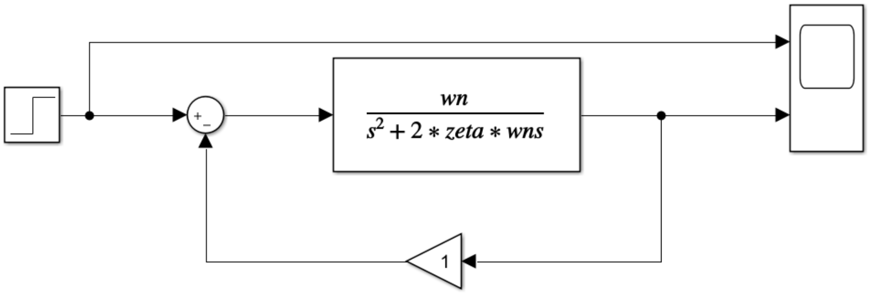

Figure 3.9: Implementation Diagram in Simulink

ii) Result:

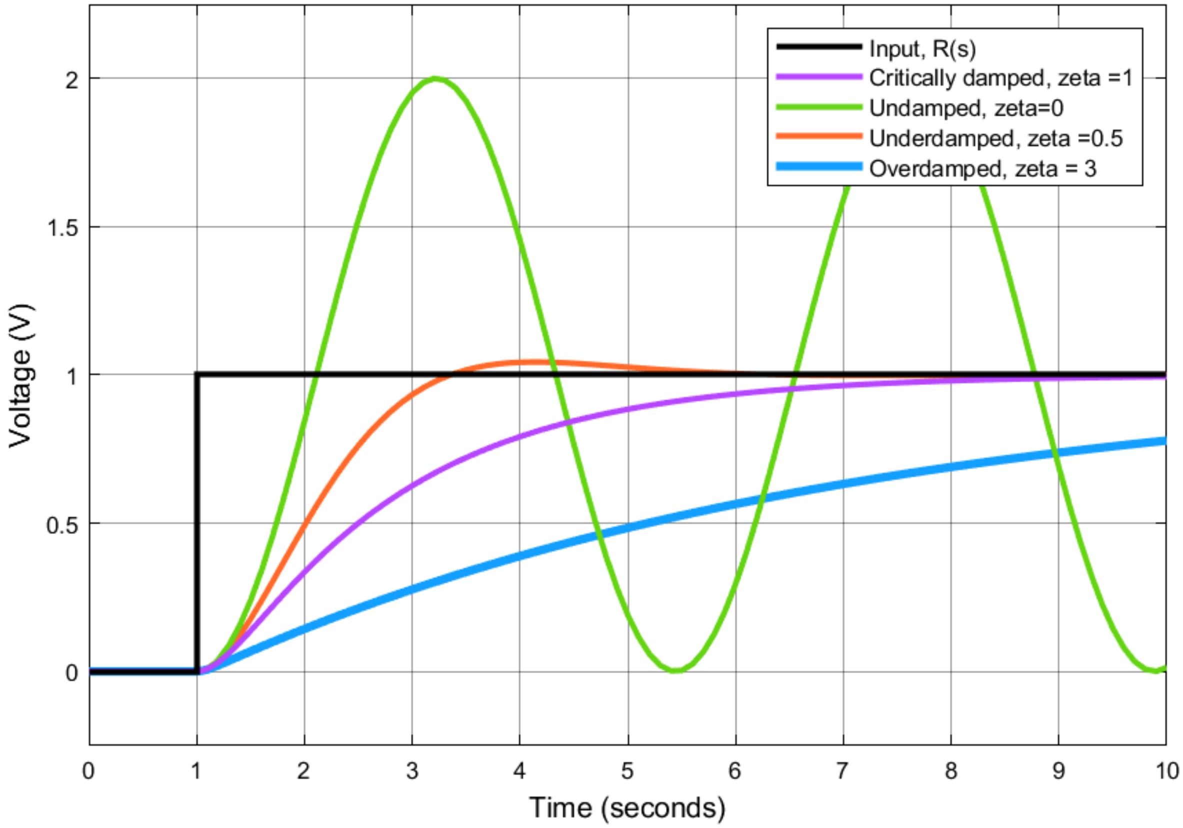

Figure 3.10: Input & Output Response of the System

Figure 3.10 represents the input and output response for the 2nd order control system. Input signal, R(s) is a unit step signal with time duration 0 to 10 sec and output response is observed for different value of damping ratio, ζ (such as – 1, 0, 0.5 & 3). According the value of ζ, a second-order system can be set into one of the four categories: i) Overdamped, when ζ >1; ii) Underdamped, when 0 < ζ < 1; iii) Undamped, when ζ=0; iv) Critically damped, when ζ=1. All of the four response categories are shown in Figure 3.10 for input step signal.

➢ **Applying a ramp signal as an input, the undamped natural frequency, ω_n=2 rad/sec and the values of damping ratio, ζ = 0.5, 0, 1 & 3 to get the output response c(t) of the 2nd order system:**

i) Implementation Diagram:

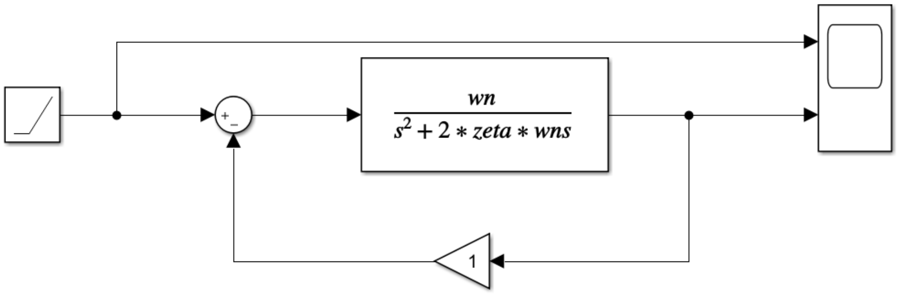

Figure 3.11: Implementation Diagram of the system

ii) Result:

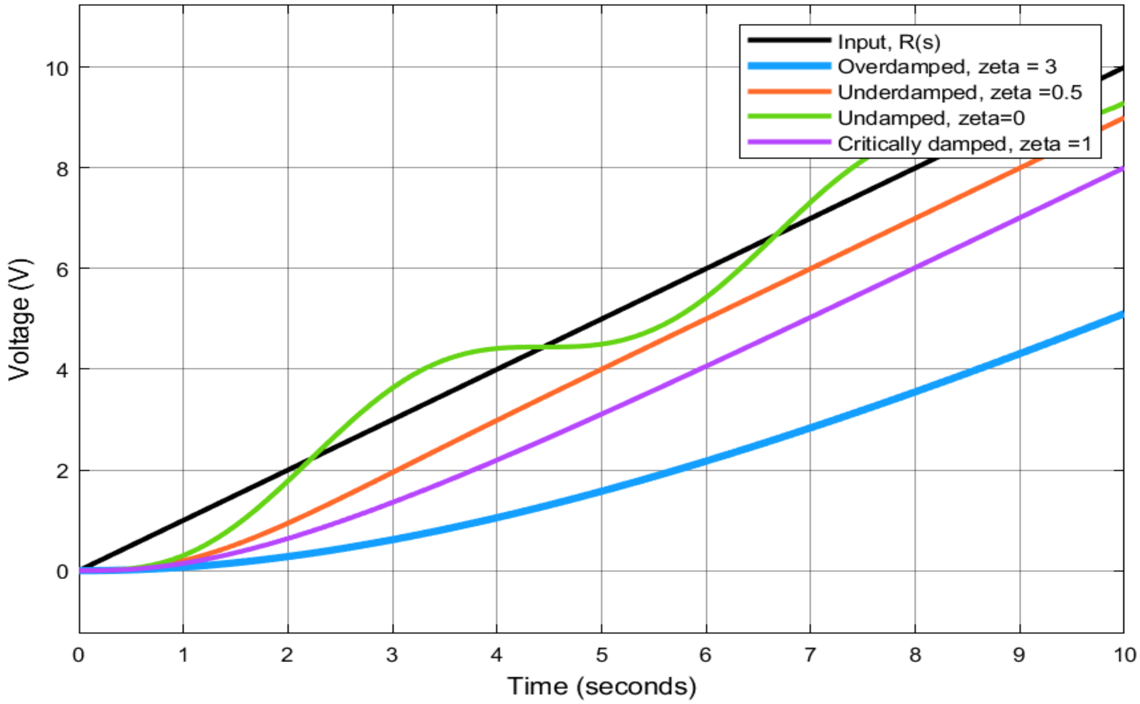

Figure 3.12: Input & Output Response

Figure 3.12 represents the input and output response for the 2nd order control system. Input signal, R(s) is a ramp signal with time duration 0 to 10 sec and output response is observed for different value of damping ratio, ζ (such as – 1, 0, 0.5 & 3). According the value of ζ, a second-order system can be set into one of the four categories: i) Overdamped, when ζ >1; ii) Underdamped, when 0 < ζ < 1; iii) Undamped, when ζ=0; iv) Critically damped, when ζ=1. All of the four response categories are shown in Figure 3.12 for input ramp signal. The output response follows the ramp input signal for all positive values of t, but there is a deviation from the input signal.

- **Applying an impulse signal as input, the undamped natural frequency, ω_n=2 rad/sec and the values of damping ratio, ζ = 0.5, 0, 1 & 3 to get the output response c(t) of the 2^{nd} order system:**

i) Implementation Diagram:

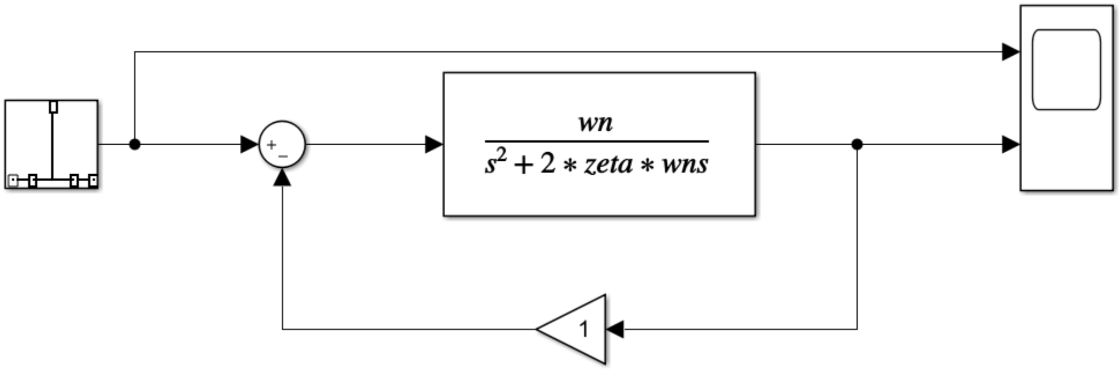

Figure 3.13: Implementation Diagram of the system

ii) Result:

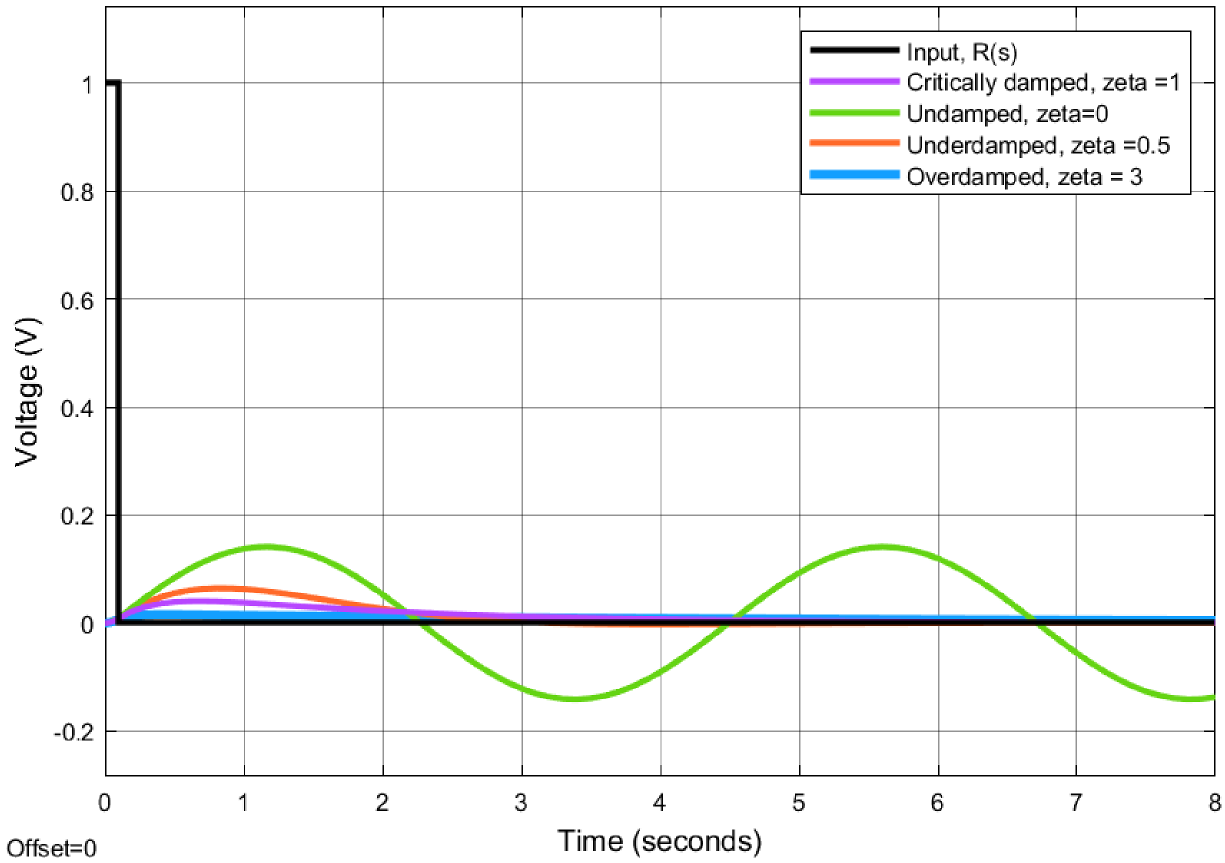

Figure 3.14: Input & Output Response

Figure 3.14 represents the input and output response for the 2nd order control system. Input signal, R(s) is an impulse signal with time duration 0 to 8 sec and output response is observed for different value of damping ratio, ζ (such as – 1, 0, 0.5 & 3). According the value of ζ, a second-order system can be set into one of the four categories: i) Overdamped, when $\zeta > 1$; ii) Underdamped, when $0 < \zeta < 1$; iii) Undamped, when $\zeta = 0$; iv) Critically damped, when $\zeta = 1$. It is not possible to describe the effect of damping ratio, ζ, since impulse response is not convenient for 2nd order control system.

Discussion: This experiment was about the characteristics of time response of the second order control system. The ability is acquired to draw the block diagram and to implement a second order system on Simulink platform from its transfer function. The effect of parameters changes on the output response of the control system was observed. Basically, the damping ratio (ζ) and the undamped natural frequency (ω_n) is varied to observe the output response of the 2nd order system. Also, the output response for different input signal (such as- unit step, unit impulse & ramp) for both control system was observed. Thus, the experiment was successfully done.

Experiment No: 04

Experiment Name: Study the Steady State Error According to the Type of the System.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the characteristics of the steady state error according to the type of the system.
2. Design type-zero, type-1 & type-2 system from its transfer function.
3. Observe the output response y(t) and the steady-state error response e(t) for different input signal (such as- unit step, ramp & parabolic).
4. Determine the Static Position Error Constant (K_p), the Static Velocity Error Constant (K_v) and the Static Acceleration Error Constant (K_a) to find steady state error theoretically.
5. Compare the theoretical results with simulated results.

Theory:
Consider the following unity feedback system whose closed-loop transfer function is

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)}$$

The transfer function between the error signal E(s) and the input signal R(s) is

$$\frac{E(s)}{R(s)} = \frac{1}{1+G(s)}$$

The final-value theorem provides a convenient way to find the steady-state performance of a stable system.

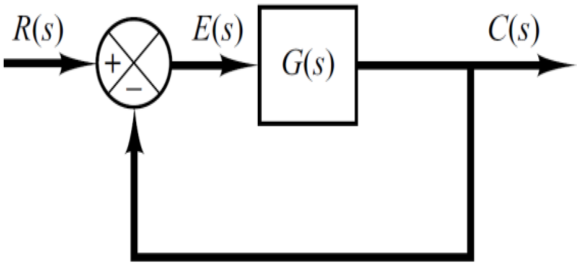

Figure 4.1: Unity Gain Feedback System

Since the error is $E(s) = \frac{1}{1+G(s)} R(s)$, the steady-state error according to the final value theorem can be defined as follows:

$$e_{ss} = \lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{sR(s)}{1+G(s)}$$

Block Diagram a type-zero system:

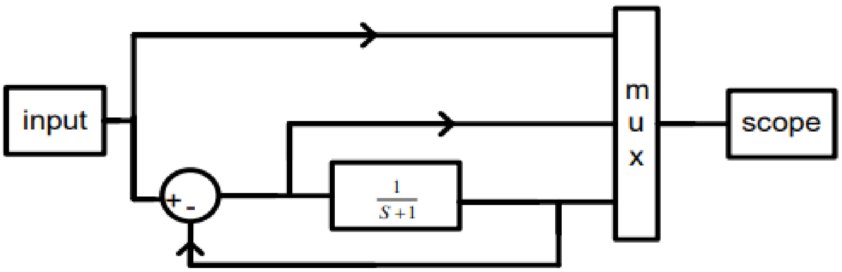

Figure 4.2: Block Diagram

Required Software: MATLAB/Simulink

Experimental Analysis:

- **Applying a unit step signal as input to get the output response y(t) and steady-state error response e(t) for a type-zero system:**

i) Implementation Diagram:

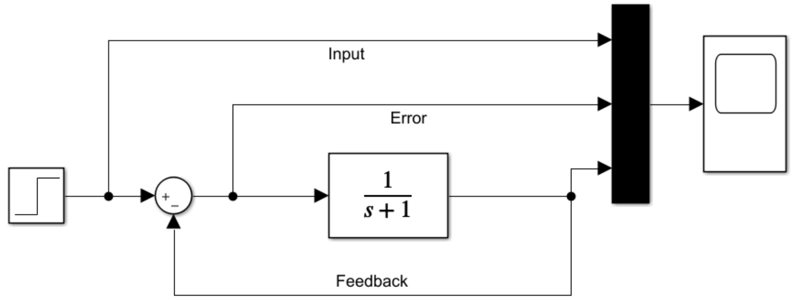

Figure 4.3: Implementation Diagram in Simulink

ii) Result:

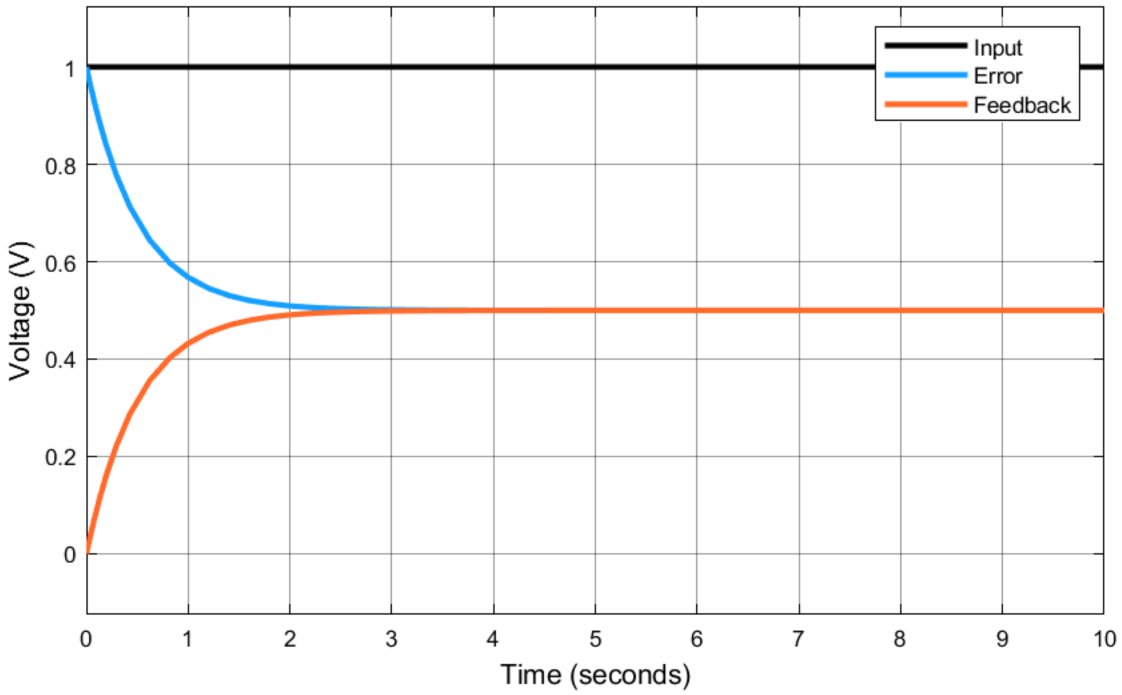

Figure 4.4: Input & Output Response

Figure 4.4 represents the input, error and feedback/output response for the 1st order type-zero system. Input signal, R(t) is a unit step signal with time duration 0 to 10 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = u(t)	$K_p = \lim_{s \to 0} G(s) = \lim_{s \to 0} \frac{1}{s+1} = 1$	$e_{ss} = \frac{1}{1+K_p} = \frac{1}{2}$

Figure 4.4 shows the value of steady-state error is 0.5 after a small transient period of 3 sec. So, the simulated result is properly agreed with the theoretical result.

- **Applying a ramp signal as input to get the output response y(t) and steady-state error response e(t) for a type-zero system:**

i) Implementation Diagram:

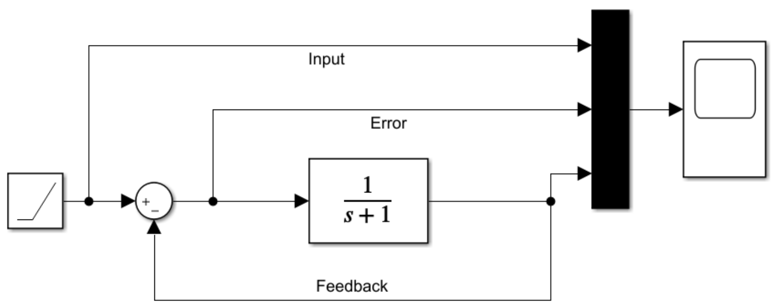

Figure 4.5: Implementation Diagram of the System

ii) Result:

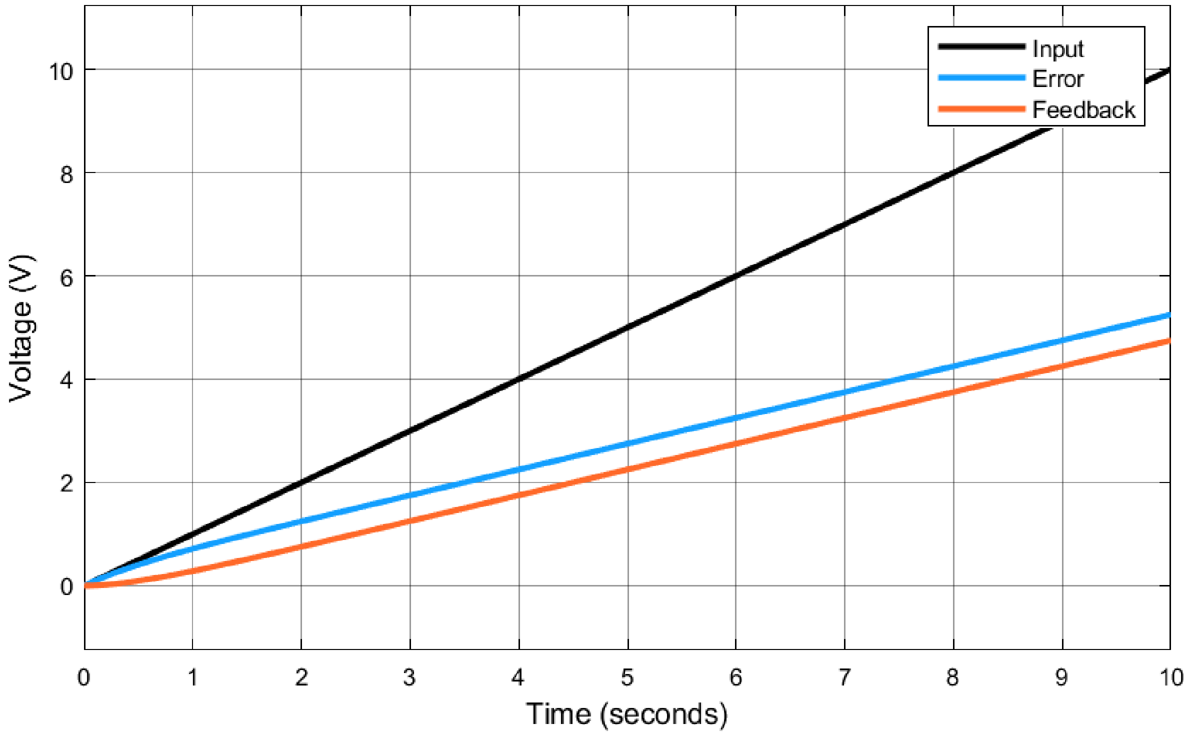

Figure 4.6: Input & Output Response

Figure 4.6 represents the input, error and feedback/output response for the 1st order type-zero system. Input signal, R(t) is a ramp signal with time duration 0 to 10 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = r(t) =t*u(t)	$\boldsymbol{K_v = \lim_{s\to 0} sG(s) = \lim_{s\to 0} (s * \frac{1}{s+1}) = 0}$	$\boldsymbol{e_{ss} = \frac{1}{K_v} = \frac{1}{0} = \infty}$

Figure 4.6 shows the value of steady-state error is gradually increasing from 0 to ∞. So, the simulated result is properly agreed with the theoretical result.

- **Applying a parabolic signal as input to get the output response y(t) and steady-state error response e(t) for a type-zero system:**

i) Implementation Diagram:

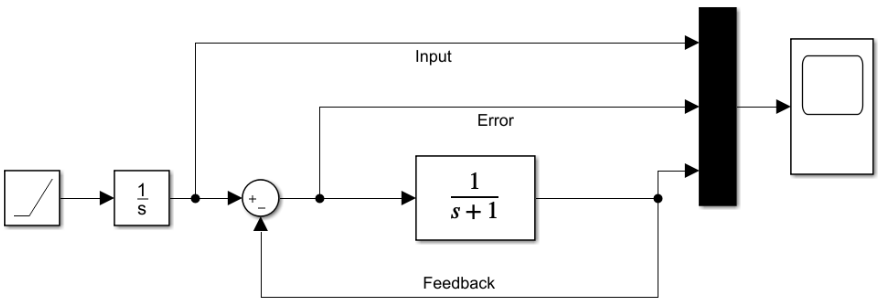

Figure 4.7: Implementation Diagram of the System

ii) Result:

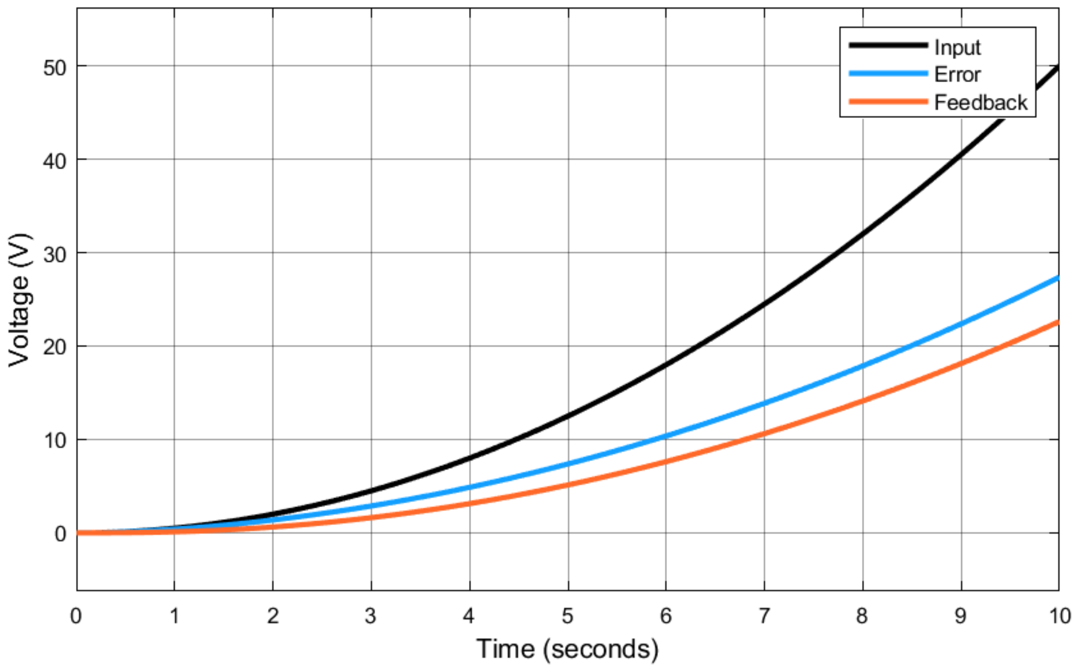

Figure 4.8: Input & Output Response

Figure 4.8 represents the input, error and feedback/output response for the 1st order type-zero system. Input signal, R(t) is a parabolic signal with time duration 0 to 10 sec. Theoretically,

Input signal	Error constant	Steady-state error
$R(t) = p(t) = \frac{t^2}{2}\, u(t)$	$K_a = \lim_{s\to 0} s^2 G(s) = \lim_{s\to 0} (s^2 * \frac{1}{s+1}) = 0$	$e_{ss} = \frac{1}{K_a} = \frac{1}{0} = \infty$

Figure 4.8 shows the value of steady-state error is gradually increasing from 0 to ∞. So, the simulated result is properly agreed with the theoretical result.

Block Diagram a type-1 system:

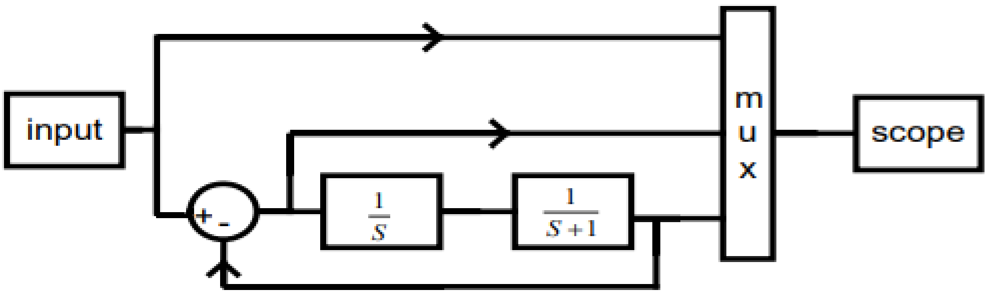

Figure 4.9: Block Diagram

- **Applying a unit step signal as input to get the output response y(t) and steady-state error response e(t) for a type-1 system:**

  i) Implementation Diagram:

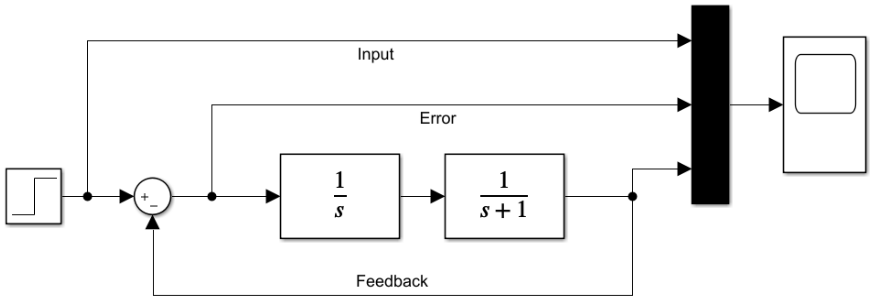

Figure 4.10: Implementation Diagram in Simulink

ii) Result:

Figure 4.11 represents the input, error and feedback/output response for the 2nd order type-1 system. Input signal, R(t) is a unit step signal with time duration 0 to 10 sec.

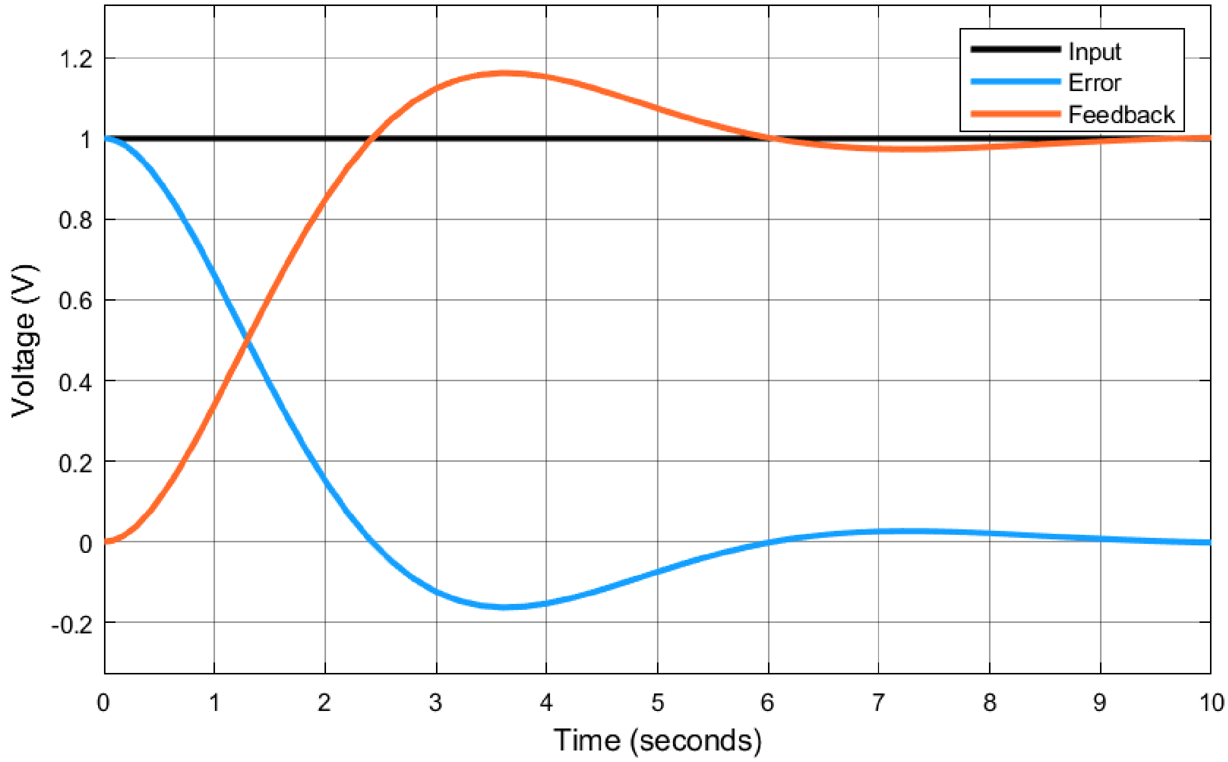

Figure 4.11: Input & Output Response

Theoretically,

Input signal	Error constant	Steady-state error
R(t) = u(t)	$K_p = \lim_{s\to 0} G(s) = \lim_{s\to 0} \frac{1}{s(s+1)} = \infty$	$e_{ss} = \frac{1}{1+K_p} = \frac{1}{\infty} = 0$

Figure 4.11 shows the value of steady-state error is 0 after a transient period of 6 sec. So, the simulated result is properly agreed with the theoretical result.

- **Applying a ramp signal as input to get the output response y(t) and steady-state error response e(t) for a type-1 system:**

  i) Implementation Diagram:

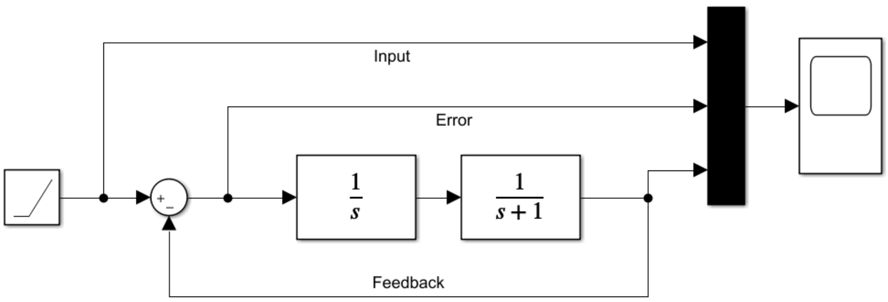

Figure 4.12: Implementation Diagram of the System

ii) Result:

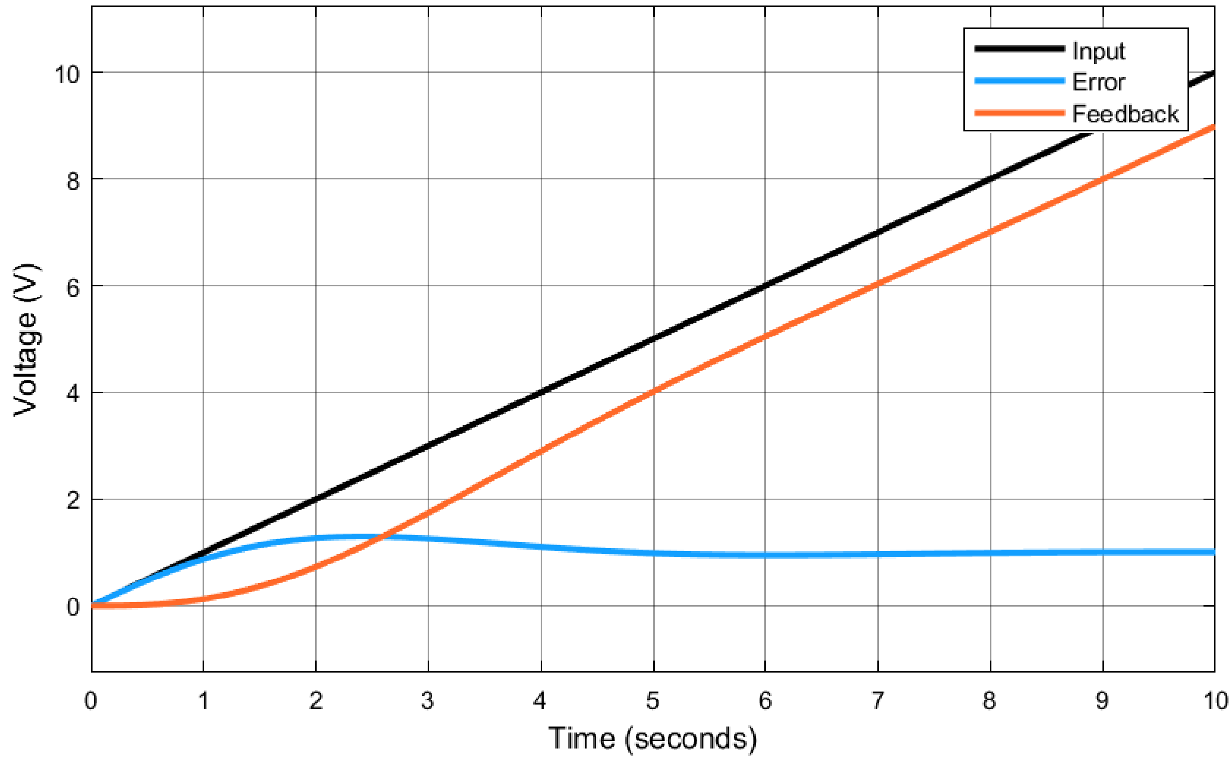

Figure 4.13: Input & Output Response

Figure 4.13 represents the input, error and feedback/output response for the 2nd order type-1 system. Input signal, R(t) is a ramp signal with time duration 0 to 10 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = r(t) =t*u(t)	$K_v = \lim_{s\to 0} sG(s) = \lim_{s\to 0} \left(s * \frac{1}{s(s+1)}\right) = 1$	$e_{ss} = \frac{1}{K_v} = \frac{1}{1} = 1$

Figure 4.13 shows the value of steady-state error is 1 after a transient period of 4 sec. So, the simulated result is properly agreed with the theoretical result.

➢ **Applying a parabolic signal as input to get the output response y(t) and steady-state error response e(t) for a type-1 system:**

i) Implementation Diagram:

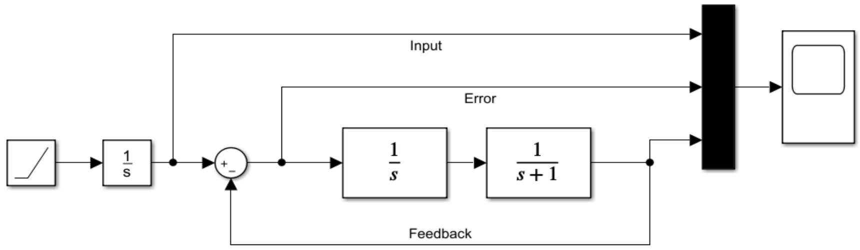

Figure 4.14: Implementation Diagram of the system

ii) Result:

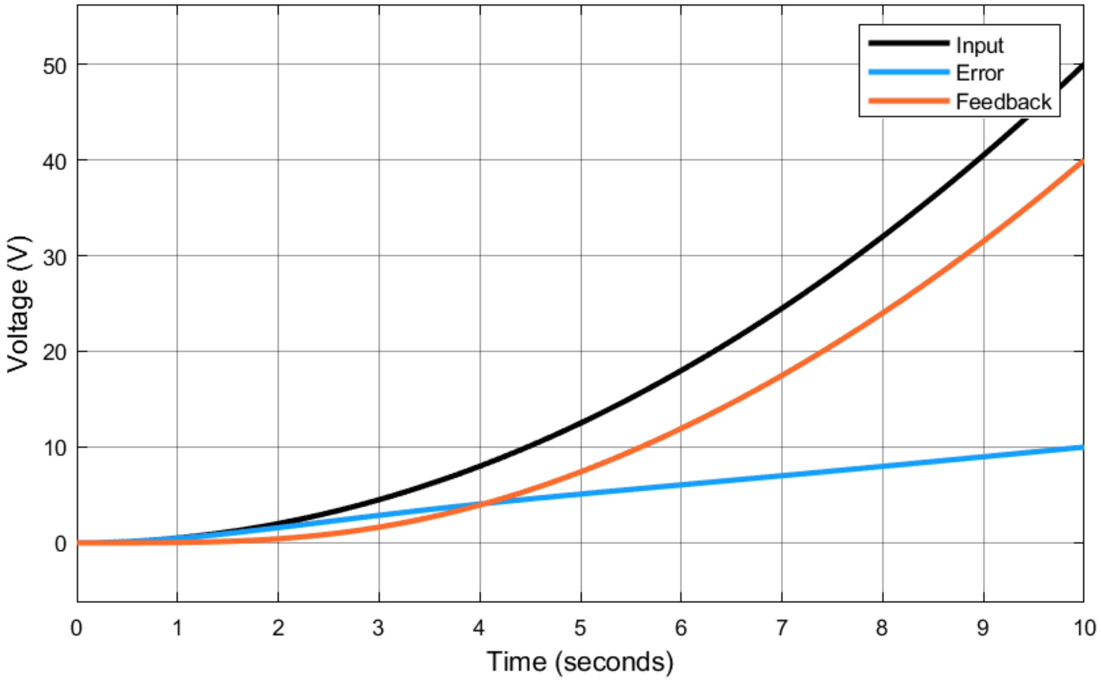

Figure 4.15: Input & Output Response

Figure 4.15 represents the input, error and feedback/output response for the 2nd order type-1 system. Input signal, R(t) is a parabolic signal with time duration 0 to 10 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = p(t) = $\frac{t^2}{2}\,u(t)$	$K_a = \lim_{s\to 0} s^2 G(s) = \lim_{s\to 0} (s^2 * \frac{1}{s(s+1)}) = 0$	$e_{ss} = \frac{1}{K_a} = \frac{1}{0} = \infty$

Figure 4.15 shows the value of steady-state error is gradually increasing from 0 to ∞. So, the simulated result is properly agreed with the theoretical result.

Block Diagram a type-2 system:

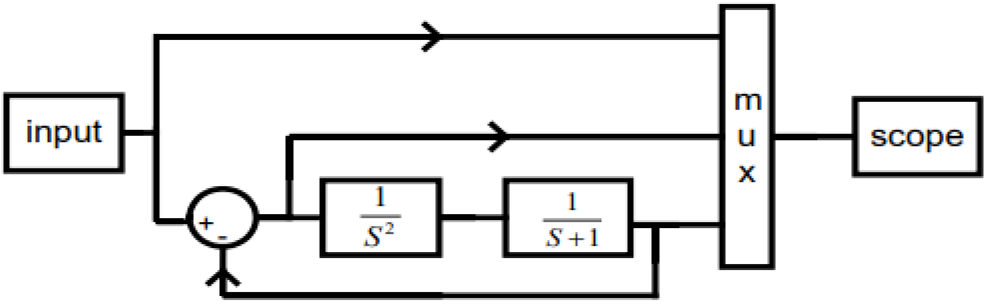

Figure 4.16: Block Diagram

- **Applying a unit step signal as input to get the output response y(t) and steady-state error response e(t) for a type-2 system:**

i) Implementation Diagram:

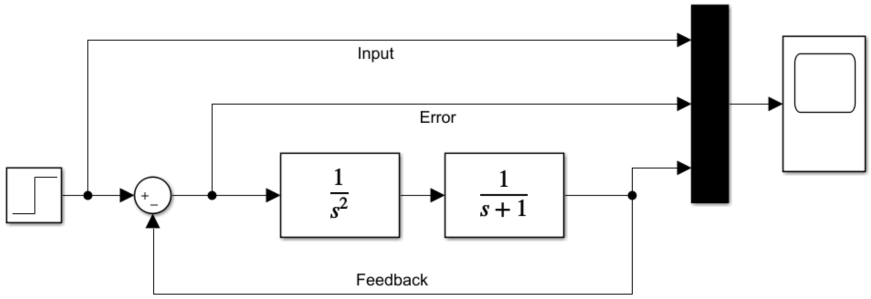

Figure 4.17: Implementation Diagram in Simulink

ii) Result:

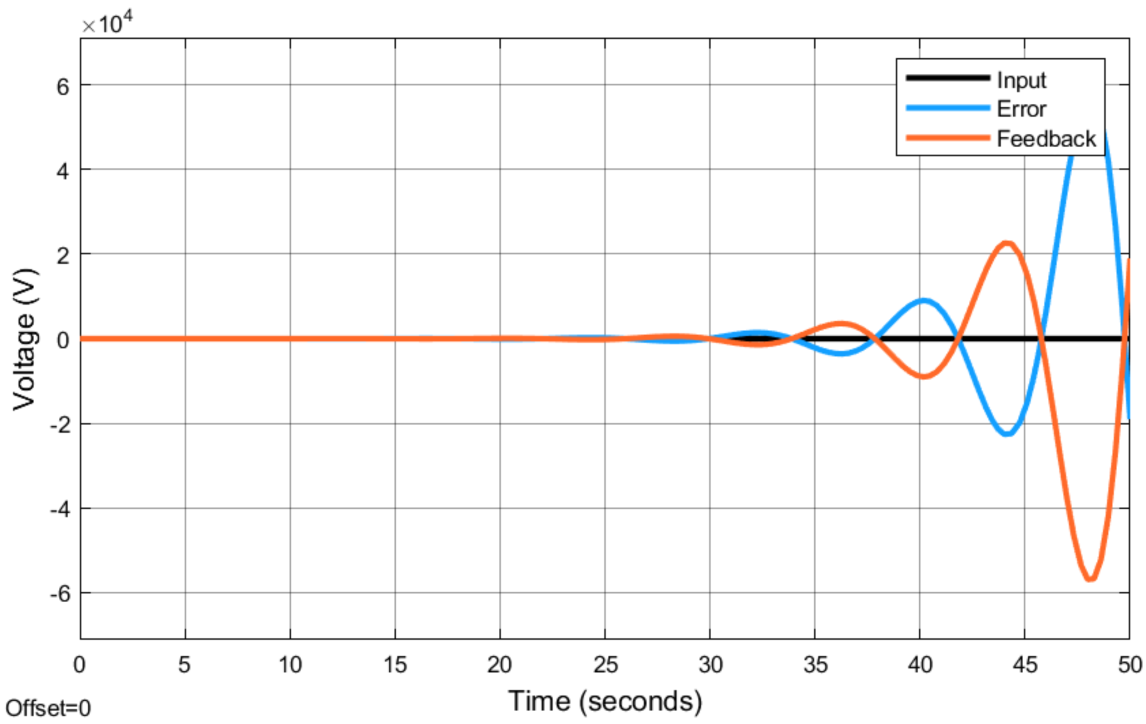

Figure 4.18: Input & Output Response

Figure 4.18 represents the input, error and feedback/output response for the 3rd order type-2 system. Input signal, R(t) is a unit step signal with time duration 0 to 50 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = u(t)	$K_p = \lim_{s\to 0} G(s) = \lim_{s\to 0} \frac{1}{s^2(s+1)} = \infty$	$e_{ss} = \frac{1}{1+K_p} = \frac{1}{\infty} = 0$

Figure 4.18 shows the value of steady-state error is 0 for a certain time, but in long run the system will become an unstable system. If pole(s) lie on imaginary axis, then the system is said to be marginally stable. So, the simulated result is not agreed with the theoretical result due to the pole(s) of the following system lies on imaginary axis.

- **Applying a ramp signal as input to get the output response y(t) and steady-state error response e(t) for a type-2 system:**

i) Implementation Diagram:

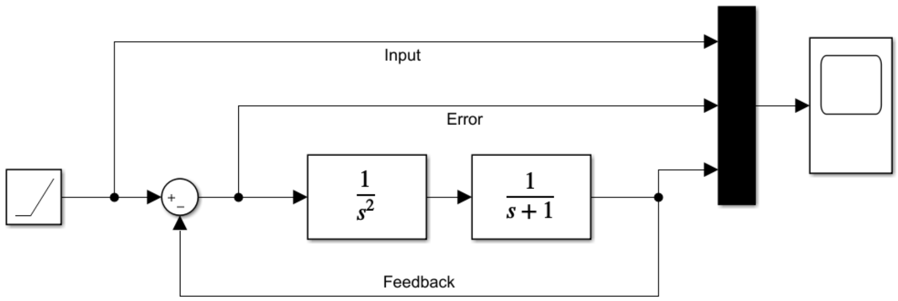

Figure 4.19: Implementation Diagram of the System

ii) Result:

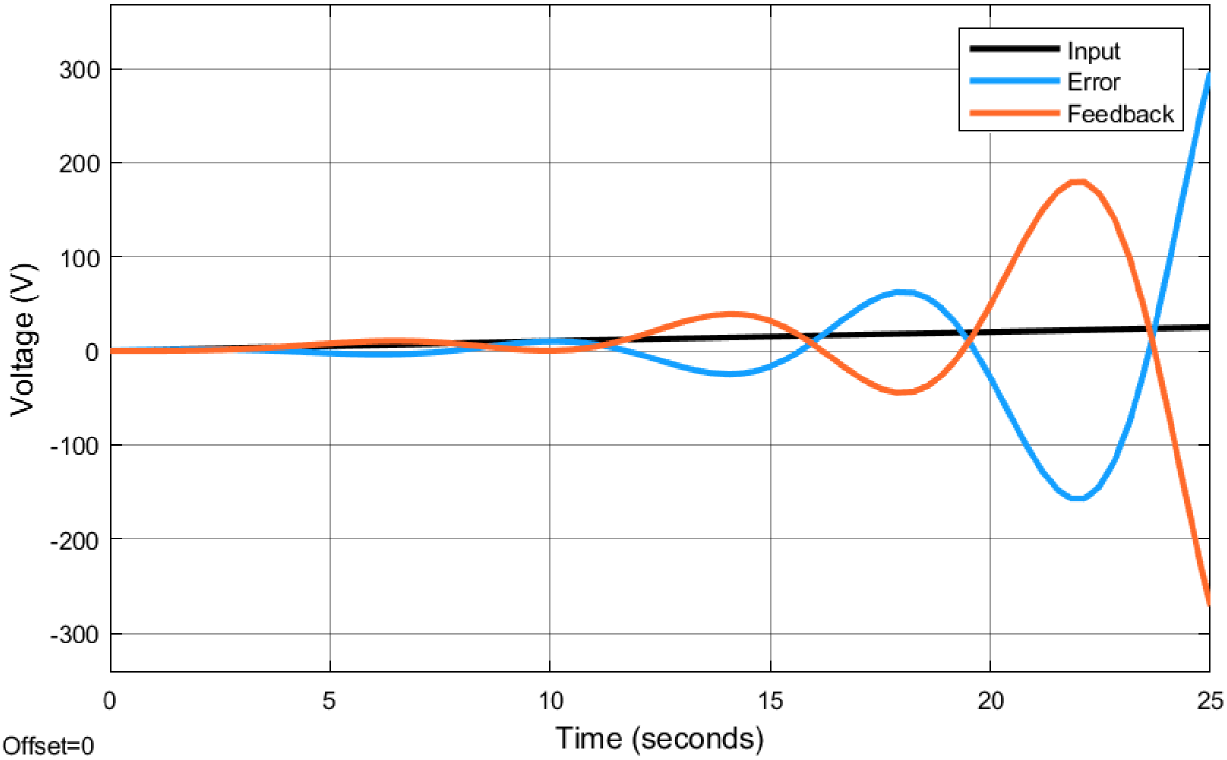

Figure 4.20: Input & Output Response

Figure 4.20 represents the input, error and feedback/output response for the 3rd order type-2 system. Input signal, R(t) is a ramp signal with time duration 0 to 25 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = r(t) =t*u(t)	$K_v = \lim_{s\to 0} sG(s) = \lim_{s\to 0} (s * \frac{1}{s^2(s+1)}) = \infty$	$e_{ss} = \frac{1}{K_v} = \frac{1}{\infty} = 0$

Figure 4.20 shows the value of steady-state error is 0 for a certain time, but in long run the system will become an unstable system. If pole(s) lie on imaginary axis, then the system is said to be marginally stable. So, the simulated result is not agreed with the theoretical result due to the pole(s) of the following system lies on imaginary axis.

- **Applying a parabolic signal as input to get the output response y(t) and steady-state error response e(t) for a type-2 system:**

i) Implementation Diagram:

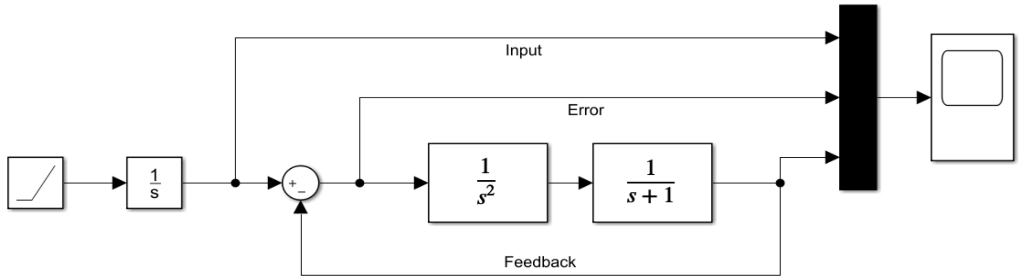

Figure 4.21: Implementation Diagram of the System

ii) Result:

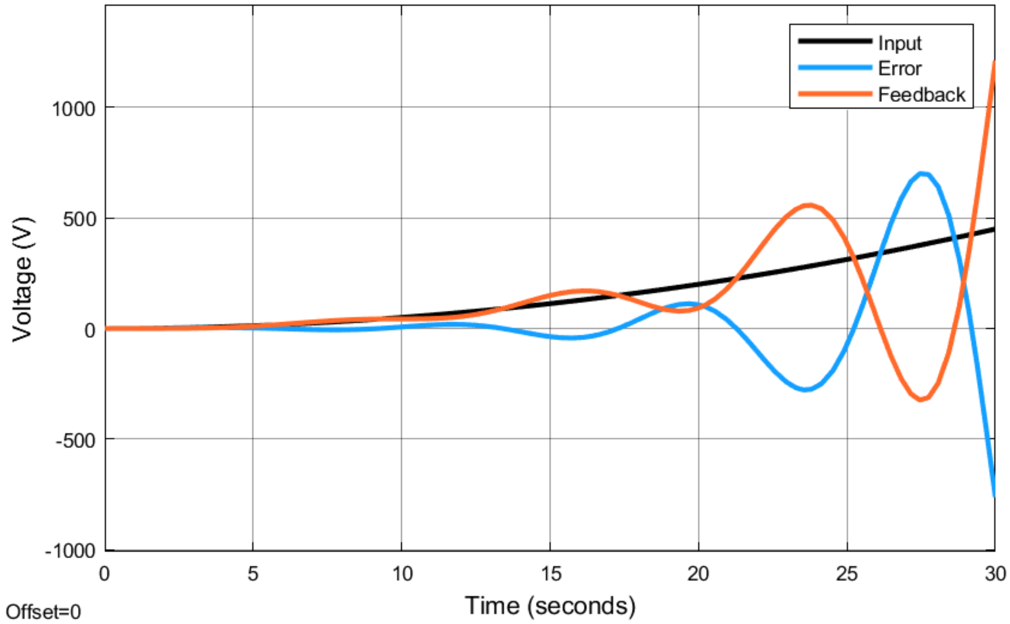

Figure 4.22: Input & Output Response

Figure 4.22 represents the input, error and feedback/output response for the 3rd order type-2 system. Input signal, R(t) is a parabolic signal with time duration 0 to 30 sec. Theoretically,

Input signal	Error constant	Steady-state error
R(t) = p(t) = $\frac{t^2}{2}\ u(t)$	$K_a = \lim_{s\to 0} s^2 G(s) = \lim_{s\to 0} (s^2 * \frac{1}{s^2(s+1)}) = 1$	$e_{ss} = \frac{1}{K_a} = \frac{1}{1} = 1$

Figure 4.22 shows the value of steady-state error is 1 for a certain time, but in long run the system will become an unstable system. If pole(s) lie on imaginary axis, then the system is said to be marginally stable. So, the simulated result is not agreed with the theoretical result due to the pole(s) of the following system lies on imaginary axis.

Discussion: This experiment was about the characteristics of the steady state error according to the type of the system. The ability is acquired to draw the block diagram and to implement type-zero, type-1 & type-2 system on Simulink platform from its transfer function. The output response y(t) and the steady-state error response e(t) for different input signal (such as- unit step, ramp & parabolic) was observed. Every physical control system inherently suffers steady-state error in response to certain types of inputs. The final-value theorem used to find the steady-state performance (theoretically) of the system which is compared with the simulated performance. It is a matter of concern that when the number of Type is increased, the system will be an unstable system due to the position of pole(s). If pole(s) lie on imaginary axis, then the system is said to be marginally stable that means the system may be unstable any instant of time. All the simulated result is properly agreed with the theoretical result excluding type-2. Thus, the experiment was successfully done.

Experiment No: 05

Experiment Name: Study the Root Locus Analysis to Investigate the Closed Loop System Stability.

Objectives:
The purpose of this experiment is:
1. To locate the closed loop poles in s-plane.
2. To investigate the closed loop system stability.
3. To analyse the system by hand calculation and plot root loci of the system step by step.
4. To compare the root loci plotted using MATLAB with hand sketch.

Theory:
A root loci plot is simply a plot of the zeros and the poles values on a graph with real and imaginary coordinates. The root locus is a curve of the location of the poles of a transfer function as some parameter is varied.

Such a plot shows clearly the contribution of each open loop pole or zero to the locations of the closed loop poles. This method is very powerful graphical technique for investigating the effects of the variation of a system parameter on the locations of the closed loop poles. The closed loop poles are the roots of the characteristic equation of the system while the locus of the roots as the gain varies from zero to infinity.

From the design viewpoint, in some systems simple gain adjustment can move the closed loop poles to the desired locations. Root loci are completed to select the best parameter value for stability. A normal interpretation of improving stability is when the real part of a pole is further left of the imaginary axis. A control system is often developed into an equation as shown below:

$$\frac{C(s)}{R(s)} = \frac{N(s)}{D(s)} = \frac{K(s-z_1)(s-z_2)\dots(s-z_m)}{(s-p_1)(s-p_2)\dots\ (s-p_m)}$$

A typical feedback system is shown in Fig. 1. The closed-loop transfer function is:

$$\frac{C(s)}{R(s)} = \frac{KG(s)}{1+G(s)H(s)}$$

The characteristic equation can be obtained by setting the denominator polynomial equal to zero, i.e.,

$$1 + G(s)H(s) = 0$$

$$\Rightarrow G(s)H(s) = -1$$

Since is a complex quantity, it can be split into angle and magnitude parts

The angle of $G(s)H(s) = -1$ of is

$$\angle G(s)H(s) = \angle -1$$

$$\Rightarrow\ G(s)H(s) =\ \pm 180°\ (2m+1)$$

where, m = 0,1,2,3…

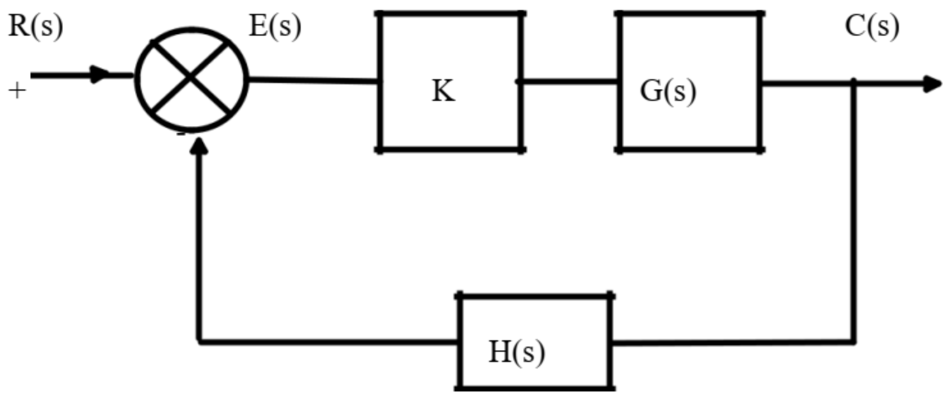

Figure 5.1: Block Diagram of a Feedback Control System

The magnitude of $G(s)H(s) = -1$ of is

$$|G(s)H(s)| = |-1|$$

$$\Rightarrow |G(s)H(s)| = 1$$

Required Software: MATLAB/Simulink

Experimental Analysis:

Task 01: The loop transfer function of a single-loop negative feedback system is

$$G(s) = \frac{K(s+3)}{s(s+4)(s+5)}$$

(i) Analyse the system, do the hand calculation and plot root loci of the system step by step.
(ii) Using MATLAB, plot the root loci again and compare will your hand sketch.
(iii) Find each value of K where system is underdamped.

Solution:

i) Step 1: Obtain the Root Loci:

Zeros: -3 Poles: $0, -4, -5$	Number of zeros, Z = 1 Number of poles, P = 3 Total Loci = max (P, Z) = 3

Step 2: Number of Asymptotes = $P - Z = 3 - 1 = 2$

Step 3: Angle of Asymptotes:

$$\psi = \frac{180\,(2x+1)}{(P-Z)}$$; where, x = 0,1… P-Z-1

$$= 90° \,\&\, 270° \quad ; when\ x = 0 \,\&\, 1$$

Step 4: Centroid of Asymptotes:

$$\sigma_c = \frac{\sum Real(P) - \sum Real(Z)}{P - Z} = \frac{(-4-5) \ -(-3)}{2} = \ -3$$

Step 5: Break-away point or break-in point:

Here, $$G(s)H(s) = \frac{K(s+3)}{s(s+4)(s+5)}$$

The characteristic equation of the system is

$$1 + \ G(s)H(s) = 1 + \frac{K(s+3)}{s(s+4)(s+5)} = 0$$

$$\Rightarrow \ s(s+4)(s+5) + \ K(s+3) = 0$$

$$\Rightarrow \ K = -\ \frac{s(s+4)(s+5)}{(s+3)}$$

The break-away point can be determined as follows:

$$\frac{dK}{ds} = -\frac{d}{ds}(\frac{s(s+4)(s+5)}{(s+3)}) = 0$$

$$\Rightarrow \ 2s^3 + 18s^2 + 54s + 60 = 0$$

$$\Rightarrow \ s = \ -4.44, -2.28 + j1.25, -2.28 - j1.25$$

Construct of Root Locus (Hand Sketch):

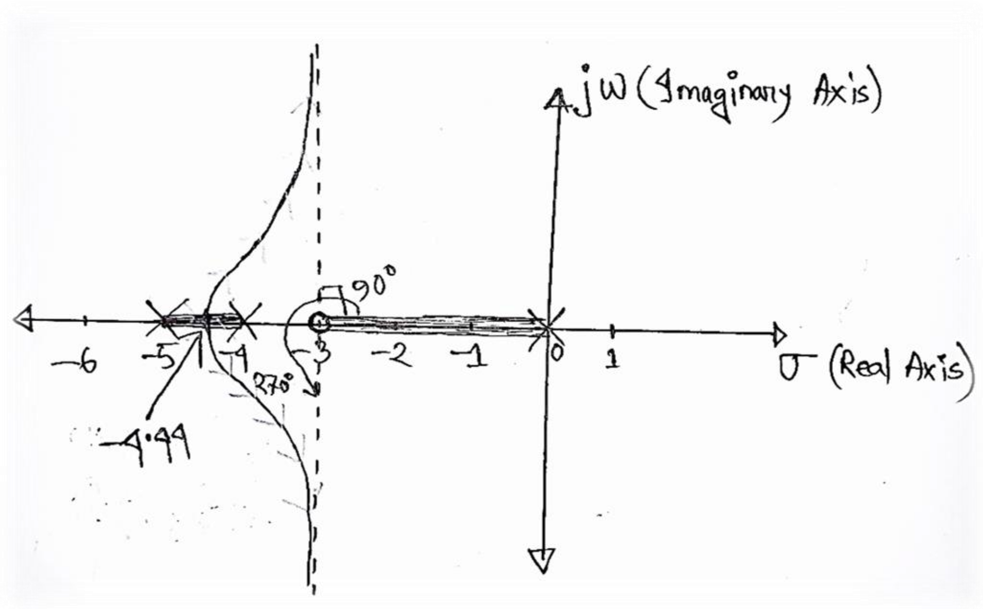

Figure 5.2: Root Locus Plot of the System

ii) Matlab Program:

```
clc;close all;clear all;
num= [1 3];
den=conv ([1 0], conv ([1 4],[1 5]));
GH=tf(num,den);
rlocus(GH);
```

Result:

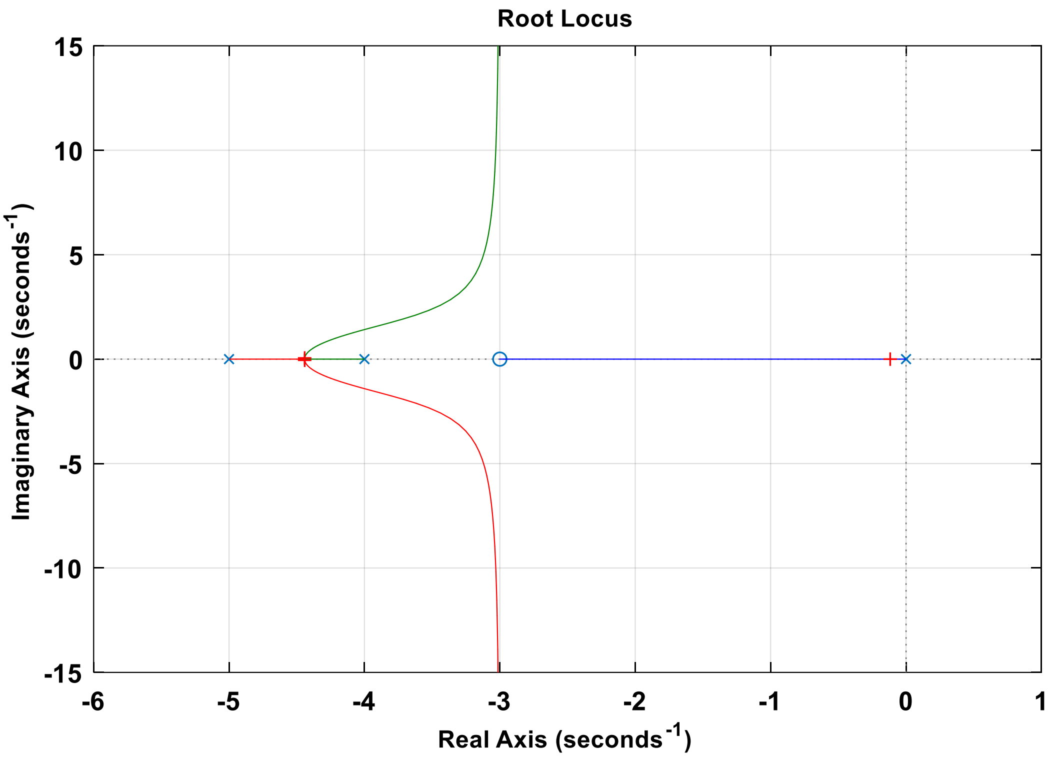

Figure 5.3: Root Locus Plot of the System

Figure 5.3 represents the root locus of the system using MATLAB and Figure 5.2 represents the root loci too by hand calculation which is entirely similar with Figure 5.3. Both figures are showing that the break-away point is -4.44 and asymptotes angle is 90° & 270°.

iii) Value of K for Underdamped System:

A system will be underdamped when the system has damping ratio, $0 < \zeta < 1$. So, the value of K will be a range of value for which system will be underdamped. Let assume, 5% maximum overshoot is acceptable for the system. Figure 5.4 shows that, we can set any one value as gain (K) for the system between 0.76 and 18.7 (i.e., $0.76 < K < 18.7$).

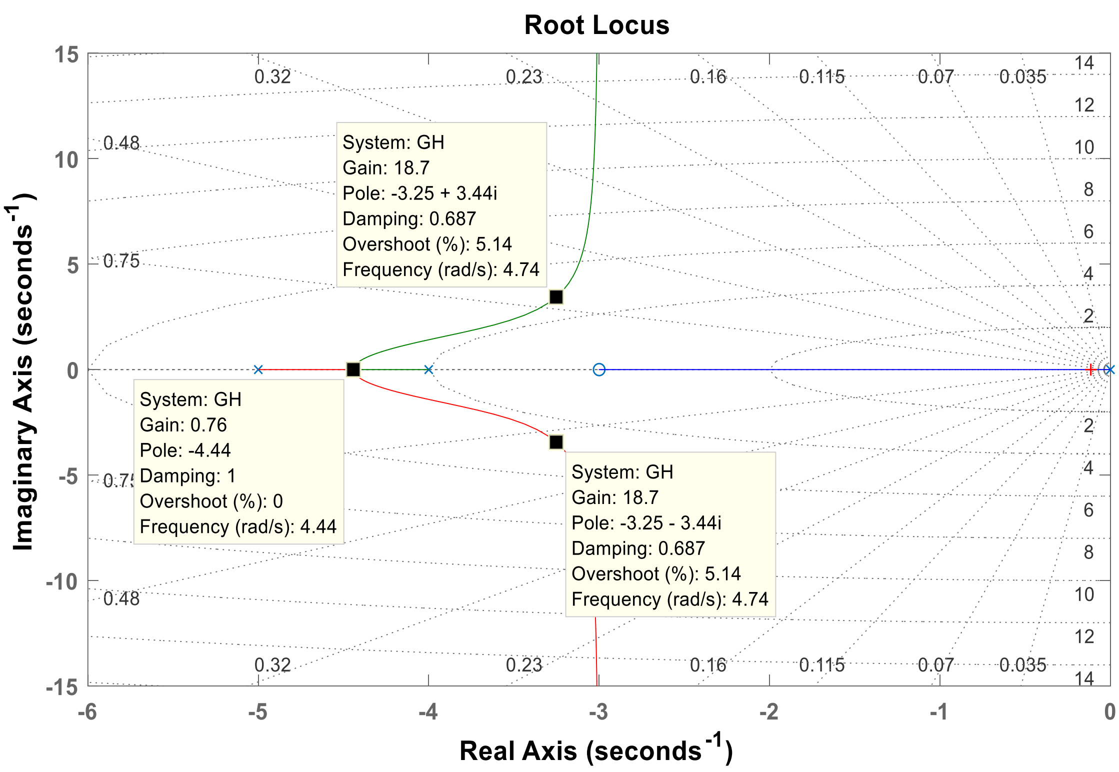

Figure 5.4: Root Locus Plot with Data Point

Task 02: The loop transfer function of a single-loop negative feedback system is

$$G(s) = \frac{K(s+2)}{s(s+3)(s^2+2s+2)}$$

(i) Analyse the system, do the hand calculation and plot root loci of the system step by step.

(ii) Using MATLAB, plot the root loci again and compare will your hand sketch.

(iii) Determine the range of feedback gain K such that the closed-loop system is stable. For each value of K where instability begins, find the corresponding frequency of oscillation.

Solution:

i) Step 1: Obtain the Root Loci:

Zeros: -2 Poles: $0, -3, -1+j, -1-j$	Number of zeros, Z = 1 Number of poles, P = 4 Total Loci = max (P, Z) = 4

Step 2: Number of Asymptotes = $P - Z = 4 - 1 = 3$

Step 3: Angle of Asymptotes:

$$\psi = \frac{180\,(2x+1)}{(P-Z)} \text{ ; where, x = 0,1… P-Z-1}$$

$$= 60°, 180° \;\&\; 300° \quad ; when\ x = 0,1 \;\&\; 2$$

Step 4: Centroid of Asymptotes:

$$\sigma_c = \frac{\sum Real(P) - \sum Real(Z)}{P-Z} = \frac{(0-3-1-1)\ -(-2)}{3} = -1$$

Step 5: Break-away point or break-in point:

Here, $G(s)H(s) = \frac{K(s+2)}{s(s+3)(s^2+2s+2)}$

The characteristic equation of the system is

$$1 + G(s)H(s) = 1 + \frac{K(s+2)}{s(s+3)(s^2+2s+2)} = 0$$

$$\Rightarrow s(s+3)(s^2+2s+2) + K(s+2) = 0$$

$$\Rightarrow K = -\frac{s(s+3)(s^2+2s+2)}{(s+2)}$$

The break-away point can be determined as follows:

$$\frac{dK}{ds} = -\frac{d}{ds}\left(\frac{s(s+3)(s^2+2s+2)}{(s+2)}\right) = 0$$

$$\Rightarrow 3s^4 + 18s^3 + 38s^2 + 32s + 12 = 0$$

$$\Rightarrow s = -0.62 \pm j0.522, -2.39 \pm j0.68$$

There is no break-away point or break-in point on real axis.

Step 6: Angle of Departure:

The angle of departure of the root locus from a complex pole can be determined as follows:

$$\varphi_d = 180° - \varphi$$

where $\varphi = \sum \varphi_P - \sum \varphi_Z$

$$= (135° + 90° + 63.44°) - (45°)$$

$$= 243.44°$$

Therefore, angle of departure at $(-1 + j1)$,

$$\varphi_d = 180° - 243.44° = -63.44°$$

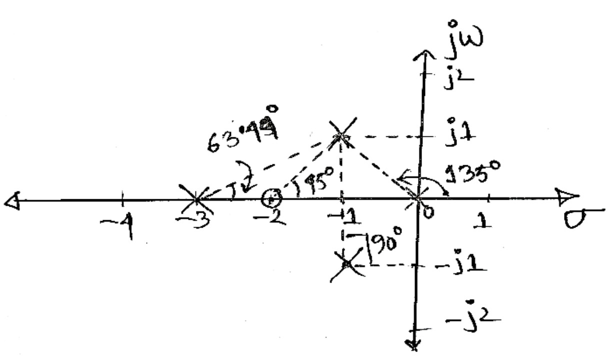

Figure 5.5: Angle of Departure

Construct of Root Locus (Hand Sketch):

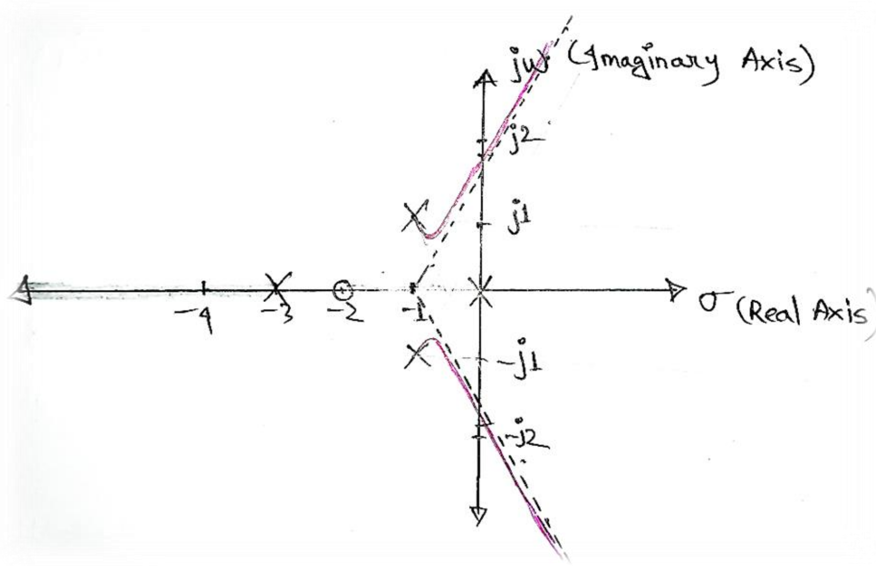

Figure 5.6: Root Locus Plot of the System

ii) Matlab Program:

```
clc;close all;clear all;
num=[1,2];
den=conv([1 0], conv([1 3],[1 2 2]));
GH=tf(num,den);
rlocus(GH);
```

Result:

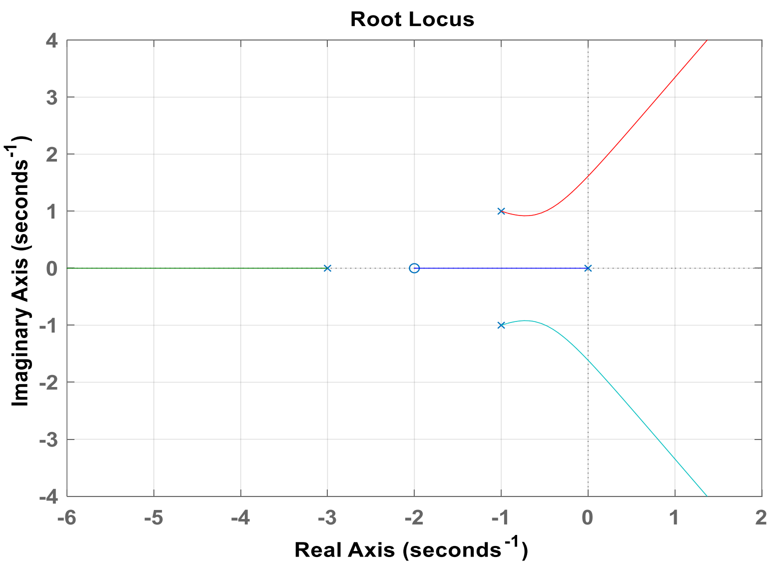

Figure 5.7: Root Locus Plot of the System

Figure 5.7 represents the root locus of the system using MATLAB and Figure 5.6 represents the root loci too by hand calculation which is entirely similar with Figure 5.7. Both figures are showing that there is no break-away point on real axis and asymptotes angle is $60°, 180°$ & $270°$.

iii) Value of K for Stable System:

A system will be unstable when the poles of the system lie on the Right Half Plane. So, the values of feedback gain (K) will be a range of value for which system will be stable. Figure 5.4 shows that, we can set the gain value between 0 and 6.49 (i.e., $0 < K < 6.49$). The instability will begin if the value of K is greater than 6.49 and the frequency of oscillation will be greater than 1.57 rad/s.

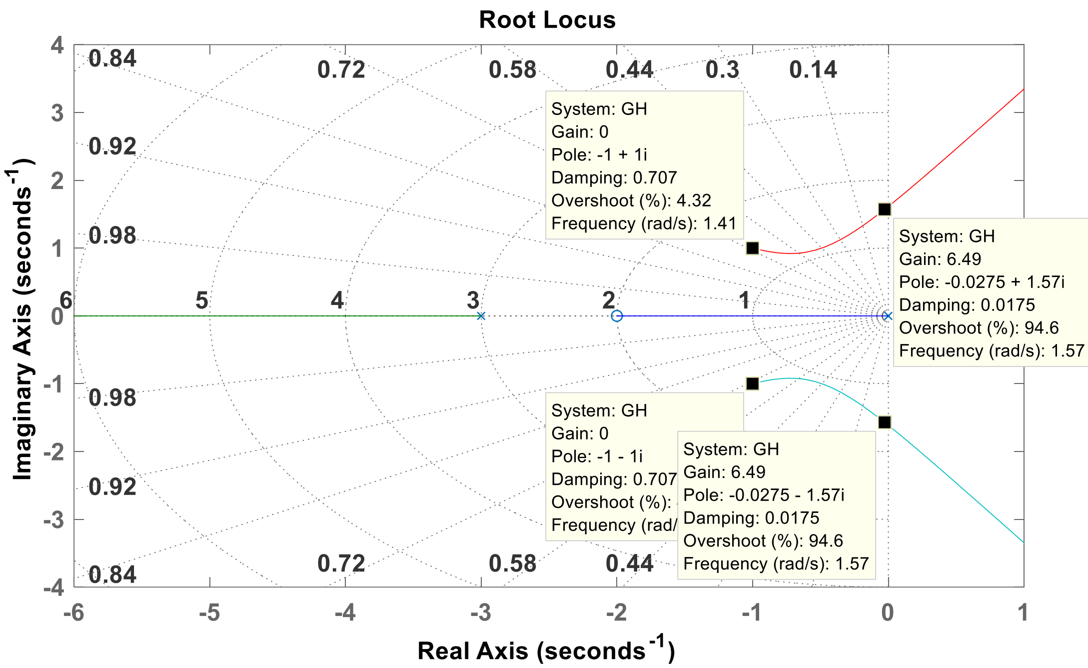

Figure 5.8: Root Locus Plot with Data Point

Discussion: In this experiment, root locus graph is plotted to investigate the closed loop system stability and to locate the closed loop poles in s-plane. The ability is acquired to draw the root locus by hand calculation and to implement it on MATLAB from its transfer function. By using the root-locus method the designer can predict the effects on the location of the closed-loop poles of varying the gain value or adding open-loop poles and/or open-loop zeros. Based on root locus graph, the value of the parameter can be chosen for the system stability and desired transient response. System stability can be determined depending on the value of K which will indicate whether the system is stable, unstable, or marginally stable. Anyone can also find whether the system is underdamped, critically damped, overdamped or undamped by observing the location of poles. The root locus graph generated by MATLAB program is properly matched with the hand sketch. Thus, the experiment was successfully done.

Experiment No: 06

Experiment Name: Study the Bode Plot to Investigate the Closed Loop System Stability.

Objectives:
The purpose of this experiment is:
1. To investigate the closed loop system stability.
2. To find the magnitude and phase plots using the hand calculation.
3. To compare the Bode plot using MATLAB with hand sketch.

Theory:
A Bode plot is a graph of the transfer function of a linear, time-invariant system versus frequency plotted with a log-frequency axis, to show the system's frequency response. It is usually a combination of a Bode magnitude plot, expressing the magnitude of the frequency response gain, and a Bode phase plot, expressing the frequency response phase shift.

Gain Margin and Phase Margin:

Consider the following system,

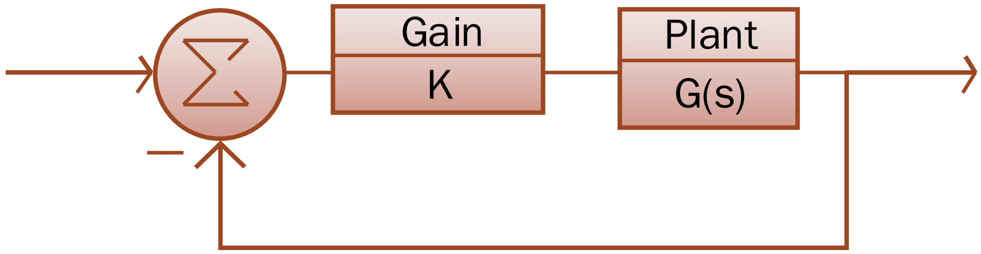

Figure 6.1: Block Diagram of a Feedback Control System

where K is a gain and G(s) is the plant.

The **gain margin** is defined as the change in open loop gain required to make the system unstable. The gain margin is the difference between the magnitude curve and 0 dB at the point corresponding to the frequency that gives a phase of -180 degree (the phase cross over frequency).

The **phase margin** is defined as the change in open loop phase shift required to make the system unstable. The phase margin is the difference between the phase curve and -180 degree at the point corresponding to the frequency that gives a gain of 0 dB (the gain cross over frequency).

The gain margin and phase margin can be directly calculated using the margin command. This command provides the gain and phase margins, the gain and phase cross over frequencies, and a graphical representation of these on the Bode plot.

Required Software: MATLAB/Simulink

Experimental Analysis:

Task 01: The loop transfer function of a single-loop negative feedback system is

$$G(s) = \frac{(s+3)}{s(s+4)(s+5)}$$

(i) Find the magnitude and phase plots using the hand calculation.
(ii) Using MATLAB, construct the Bode plot and determine the gain and phase margins of the system.
(iii) Determine whether the system is stable or unstable.

Solution:

i) Step 1: Given, The loop transfer function,

$$G(s) = \frac{(s+3)}{s(s+4)(s+5)} = \frac{\frac{3}{20}\,(1+\frac{s}{3})}{s(1+\frac{s}{4})(1+\frac{s}{5})}$$

Put $s = j\omega$ in the transfer function,

$$G(j\omega) = \frac{\frac{3}{20}\,(1+\frac{j\omega}{3})}{j\omega(1+\frac{j\omega}{4})(1+\frac{j\omega}{5})}$$

Step 2: Magnitude, M = $|G(j\omega)|$

$$= 20 log\frac{3}{20} - 20\log|j\omega| + 20\, log\left|1+\frac{j\omega}{3}\right| - 20\, log\left|1+\frac{j\omega}{4}\right| - 20\, log\left|1+\frac{j\omega}{5}\right|$$

$$= -16.48 - 20\log\omega + 20\, log\sqrt{1+\frac{\omega^2}{9}} - 20\, log\sqrt{1+\frac{\omega^2}{16}} - 20\, log\sqrt{1+\frac{\omega^2}{25}}$$

Phase Angle, $\varphi = -90° + \tan^{-1}\frac{\omega}{3} - \tan^{-1}\frac{\omega}{4} - \tan^{-1}\frac{\omega}{5}$

Table 6.1: Values for magnitude plot:

Sl. No.	Factor	Corner Frequency, ω_c	Slope	Resultant Slope
01	$\frac{3}{20} = 20log\frac{3}{20} = -16.48$ dB	None	0 dB/dec	0 dB/dec
02	$\frac{1}{j\omega} = -20\log\omega$	None	-20 dB/dec	-20 dB/dec
03	$1+\frac{j\omega}{3} = 20\, log\sqrt{1+\frac{\omega^2}{9}}$	3 rad/sec	+20 dB/dec	0 dB/dec

04	$1+\frac{j\omega}{4} = -20\,log\sqrt{1+\frac{\omega^2}{16}}$	**4 rad/sec**	**-20 dB/dec**	**-20 dB/dec**
05	$1+\frac{j\omega}{5} = -20\,log\sqrt{1+\frac{\omega^2}{25}}$	**5 rad/sec**	**-20 dB/dec**	**-40 dB/dec**

Table 6.2: Values for phase plot:

Frequency, ω_c (rad/ sec)	**0.1**	**1**	**10**	**100**	**∞**
Phase, φ	$-90.67°$	$-96.91°$	$-148.33°$	$-176.57°$	$-180°$

Construct of Bode Plot (Hand Sketch):

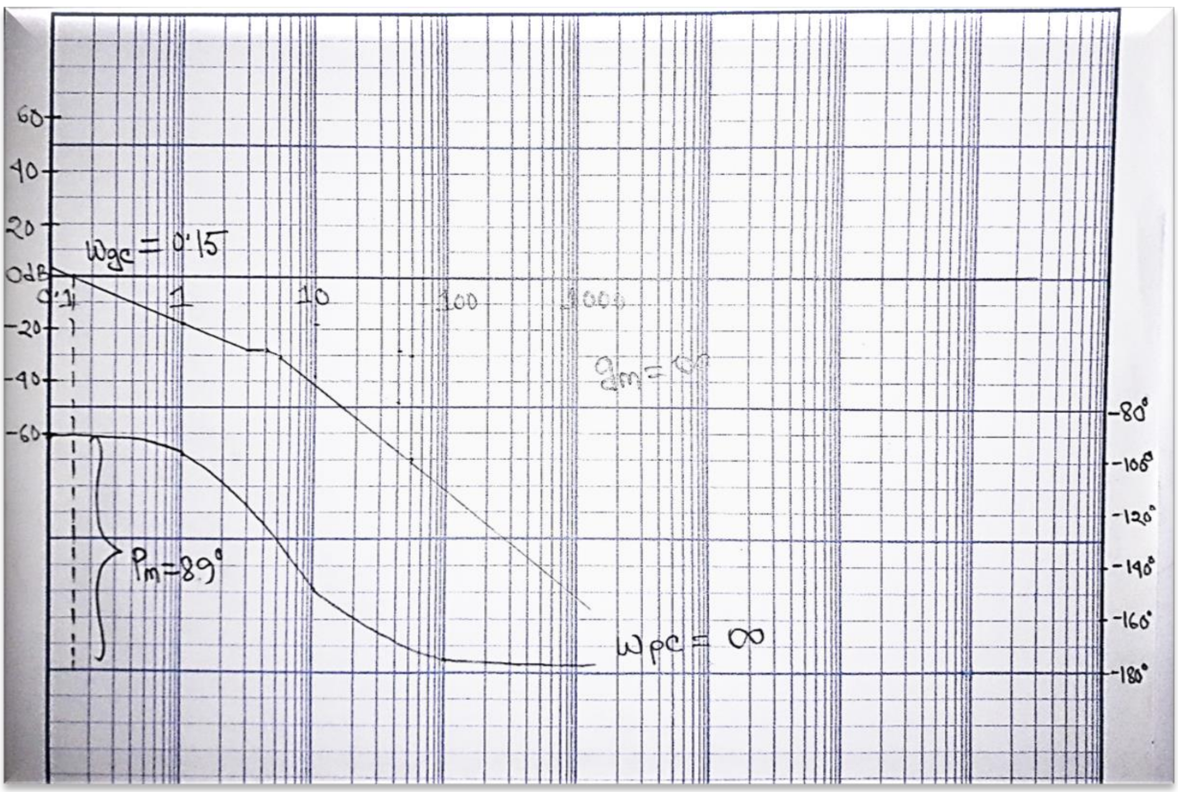

Figure 6.2: Bode Plot of the System

ii) Matlab Program:

```
clc;close all;clear all;
num=[1 3];
den=[1 9 20 0];
margin(num,den)
```

Result:

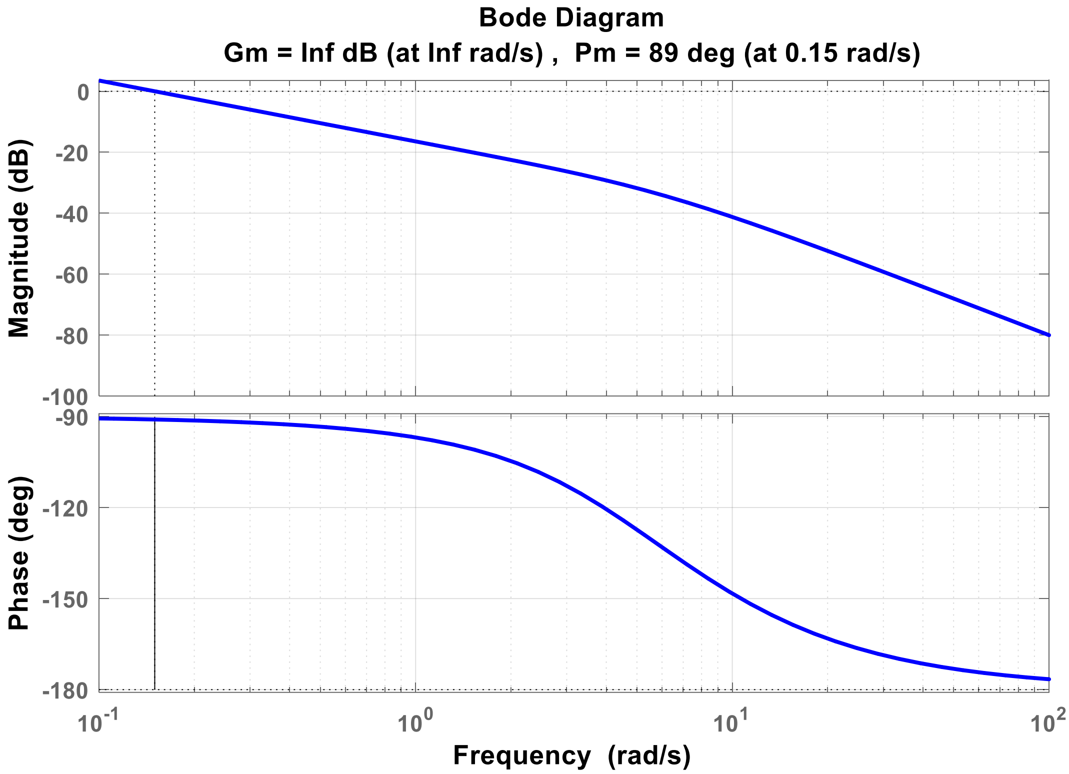

Figure 6.3: Bode Plot of the System

Figure 6.3 represents the bode plot of the system using MATLAB and Figure 6.2 represents the bode plot too by hand calculation which is entirely similar with Figure 6.3. Both figures are showing that the gain margin is infinite ($G_m = \infty\ dB$) and phase margin, P_m is 89° .

iii) Stability of the System:

A system is stable when phase margin and gain margin (both) are positive (i.e., $\omega_{pc} > \omega_{gc}$). Figure 6.3 shows that gain crossover frequency, $\omega_{gc} = 0.15$ rad/sec and phase crossover frequency, $\omega_{pc} = \infty$ rad/sec. So, the system is inherently **stable**.

Task 02: The loop transfer function of a single-loop negative feedback system is

$$G(s) = \frac{(s+2)}{s(s+3)(s^2+2s+2)}$$

(i) Find the magnitude and phase plots using the hand calculation.
(ii) Using MATLAB, construct the Bode plot and determine the gain and phase margins of the system.
(iii) Determine whether the system is stable or unstable.

Solution:

i) Step 1: Given, The loop transfer function,

$$G(s) = \frac{(s+2)}{s(s+3)(s^2+2s+2)} = \frac{\frac{1}{3}\,(1+\frac{s}{2})}{s(1+\frac{s}{3})(1+s+\frac{s^2}{2})}$$

Put $s = j\omega$ in the transfer function,

$$G(j\omega) = \frac{\frac{1}{3}\,(1+\frac{j\omega}{2})}{j\omega(1+\frac{j\omega}{3})(1+j\omega-\frac{\omega^2}{2})} = \frac{\frac{1}{3}\,(1+\frac{j\omega}{2})}{j\omega(1+\frac{j\omega}{3})(1+2\,j\left(\frac{\sqrt{2}}{2}\right)\left(\frac{\omega}{\sqrt{2}}\right)+(\frac{j\omega}{\sqrt{2}})^2)}$$

Step 2: Magnitude, M = $|G(j\omega)|$

$$= 20log\frac{1}{3} - 20\log|j\omega| + 20\,log\left|1+\frac{j\omega}{2}\right| - 20\,log\left|1+\frac{j\omega}{3}\right| - 40\,log\left|1+j\omega-\frac{\omega^2}{2}\right|$$

$$= -9.54 - 20\log\omega + 20\,log\sqrt{1+\frac{\omega^2}{4}} - 20\,log\sqrt{1+\frac{\omega^2}{9}} - 40\,log\sqrt{1+\omega^2-((\frac{\omega}{\sqrt{2}})^2)^2}$$

Phase Angle, $\varphi = -90° + \tan^{-1}\frac{\omega}{2} - \tan^{-1}\frac{\omega}{3} - \tan^{-1}\frac{\omega}{1--\frac{\omega^2}{2}}$

Table 6.3: Values for magnitude plot:

Sl. No.	Factor	Corner Frequency, ω_c	Slope	Resultant Slope
01	$\frac{1}{3} = 20log\frac{1}{3} = -9.54$ dB	None	0 dB/dec	0 dB/dec
02	$\frac{1}{j\omega} = -20\log\omega$	None	-20 dB/dec	-20 dB/dec

03	$1 + j\omega - \frac{\omega^2}{2} = -40\ log \sqrt{1 + \omega^2 - ((\frac{\omega}{\sqrt{2}})^2)^2}$	$\sqrt{2} = 1.414$	**-40 dB/dec**	**-60 dB/dec**
04	$1 + \frac{j\omega}{2} = 20\ log \sqrt{1 + \frac{\omega^2}{4}}$	**2 rad/sec**	**+20 dB/dec**	**-40 dB/dec**
05	$1 + \frac{j\omega}{3} = -20\ log \sqrt{1 + \frac{\omega^2}{9}}$	**3 rad/sec**	**-20 dB/dec**	**-60 dB/dec**

Table 6.4: Values for phase plot:

Frequency, ω_c (rad/ sec)	**0.1**	**1**	1.4	**2**	**10**
Phase, φ	$-94.79°$	$-145.31°$	$-169.21°$	$-15.26° - 180° = 195.26°$	$-73.07° - 180° = -253.07°$

Construct of Bode Plot (Hand Sketch):

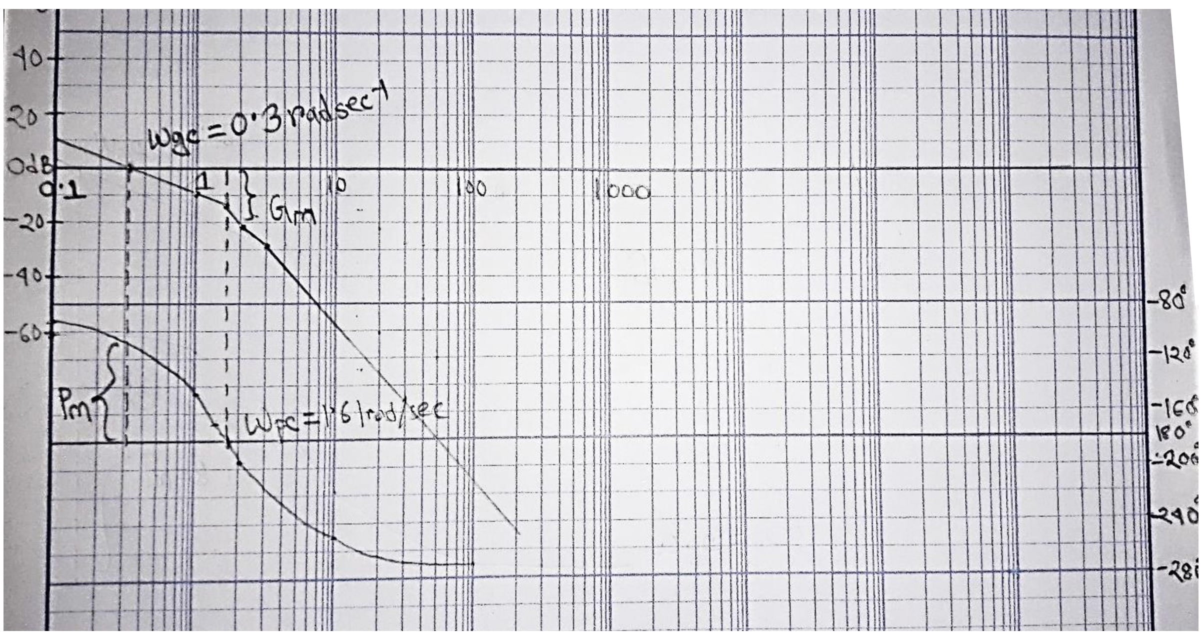

Figure 6.4: Bode Plot of the System

ii) Matlab Program:

```
clc;close all;clear all;
num=[1 2];
den=[1 5 8 6 0];
sys=tf(num,den)
margin(num,den)
```

Result:

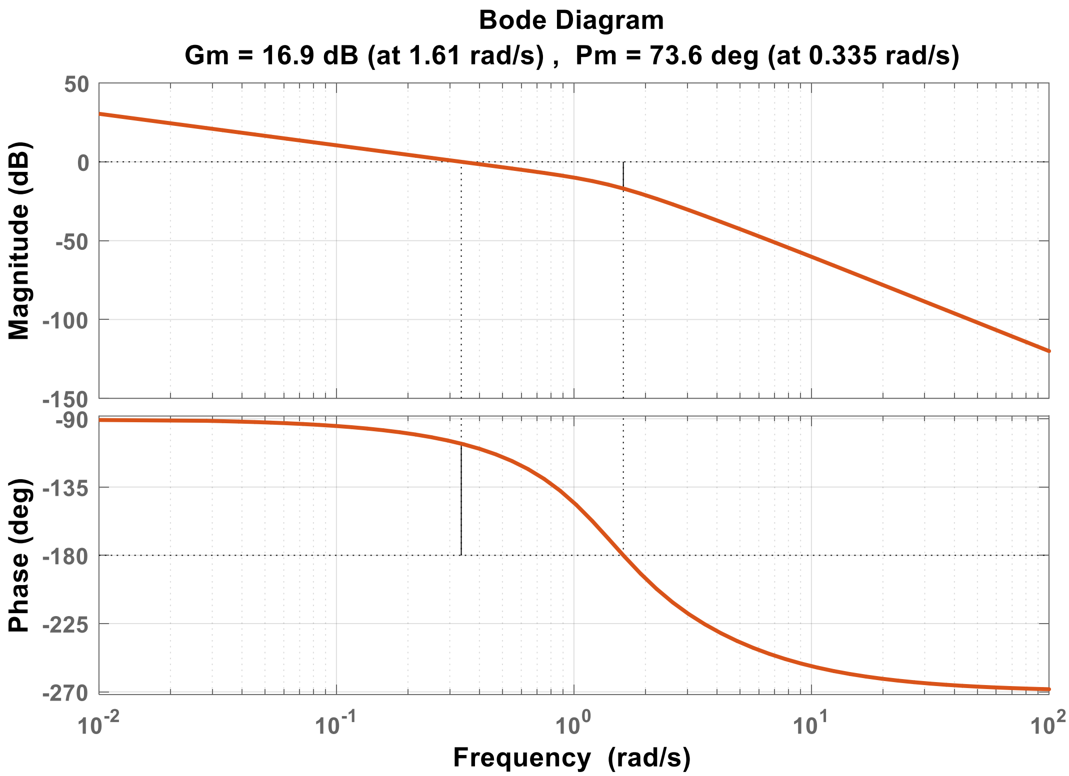

Figure 6.5: Bode Plot of the System

Figure 6.5 represents the bode plot of the system using MATLAB and Figure 6.4 represents the bode plot too by hand calculation which is entirely similar with Figure 6.5. Both figures are showing that the gain margin is 16.9 dB ($i.e., G_m = 16.9\ dB$) and phase margin, P_m is $73.6°$.

iii) Stability of the System:

A system is stable when phase margin and gain margin (both) are positive (i.e., $\omega_{pc} > \omega_{gc}$). Figure 6.5 shows that gain crossover frequency, $\omega_{gc} = 0.335$ rad/sec and phase crossover frequency, $\omega_{pc} = 1.61$ rad/sec. So, the system is **stable**.

Discussion: In this experiment, closed loop stability is investigated using bode plot. The ability is acquired to draw the bode plot by hand calculation and to implement it on MATLAB from its transfer function. To verify the hand sketch, MATLAB is used. The stability of closed loop systems can be determined by observing the behaviour of magnitude and phase plots against the frequency (ω). By using the bode plot the designer can determine whether the system is stable, unstable, or marginally stable depending on the value of gain margin and phase margin. A system is stable when phase margin and gain margin (both) are positive (i.e., $\omega_{pc} > \omega_{gc}$). Thenceforth, designer can predict the required compensator by the help of bode plot. The magnitude and phase plot generated by MATLAB program is properly matched with the hand sketch. Thus, the experiment was successfully done.

Experiment No: Extra - 01

Experiment Name: Simulation and Analysis of Buck, Boost, and Buck-Boost Converter.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the operations and characteristics of DC-DC converter.
2. Design different types of switching converter - Buck, Boost and Buck-Boost for specific input output voltage by changing capacitor, inductor values.
3. Observe the input, output waveform, gate pulse of the Converters using MATLAB Simulink.

Theory:
Dc-dc converters are power electronic circuits that convert a dc voltage to a different dc voltage level, often providing a regulated output. In a switching converter circuit, the transistor/ IGBT/ thyristor/MOSFET operates as an electronic switch by being completely on or completely off (saturation or cutoff for a BJT or the triode and cutoff regions of a MOSFET). This circuit is also known as a dc chopper. There are two types of dc chopper: i) Step Up & ii) Step Down.
Most commonly used switch mode regulators –
- ❖ Buck Converter
- ❖ Boost Converter
- ❖ Buck-Boost Converter and
- ❖ Ćuk Converter

All of that converter is simulated here with proper circuit diagram, input output waveform, gate pulse.

Required Software: MATLAB/Simulink

Experimental Analysis:

- ❖ **Buck Converter**

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while drawing less average current) from its input (supply) to its output (load).

- When the switch S is ON, the diode D1 is OFF as it is reverse biased. The current flows through the inductor to the load.
- When the switch is OFF, the diode becomes forward biased because of the negative inductor voltage. Diode D1 provides path for the load current to flow when the switch S is OFF and improves the load current waveform. Furthermore, by maintaining the continuity of the load current at turn-off, it prevents transient voltage from appearing across the switch, due to sudden change of the load current.

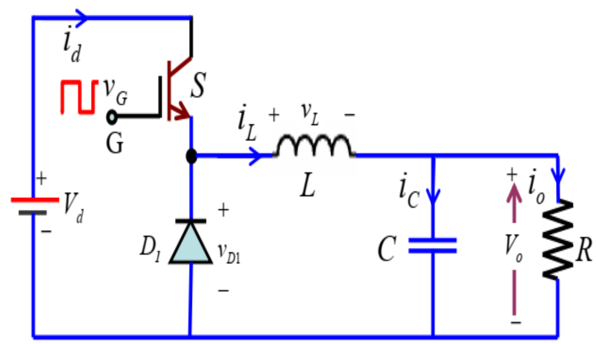

Figure. 1.1: Buck converter

Design parameters for the Buck converter:

Input Voltage ($V_{in\,(dc)}$) = 40 V	Switching Frequency, f= 10kHz
Output Voltage ($V_{o\,(avg)}$) = 20 V	Voltage Ripple ($\frac{\Delta V_o}{V_o}$) = 5%, 0.5%, 10%, 2%, 1%
Duty Cycle, D = V_o/V_{in} = 20 / 40 = 0.5	Current Ripple (ΔI) = 5%
$\boldsymbol{L_{min} = \frac{(1-D)R}{2f} = 3.75\,mH \approx 4.68\,mH}$	$C = \frac{1-D}{8L(\frac{\Delta V_o}{V_o})f^2} = 3.3, 26, 1.33, 6.67, 13\ \mu F$
Load, R = 150 Ω	

i) Implementation Diagram:

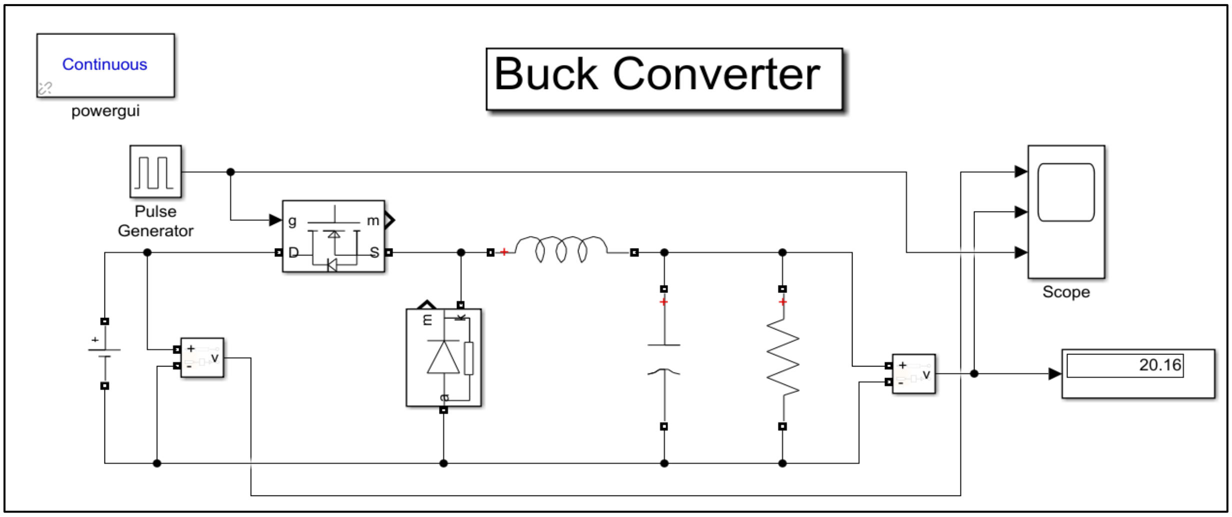

Figure 1.2: Buck Converter

ii) Result:

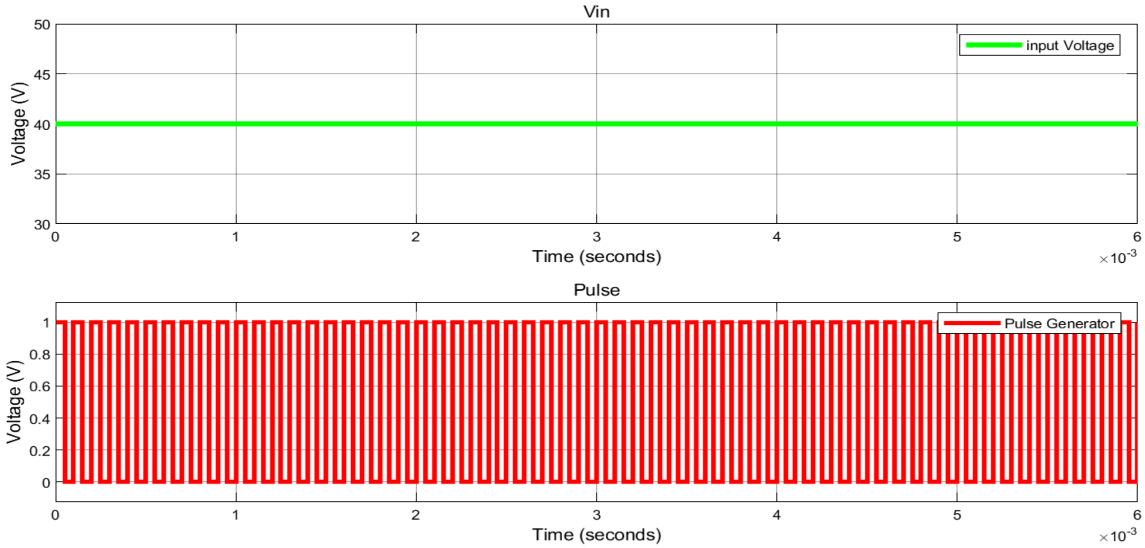

Figure 1.3: Input signal & Gate Pulse

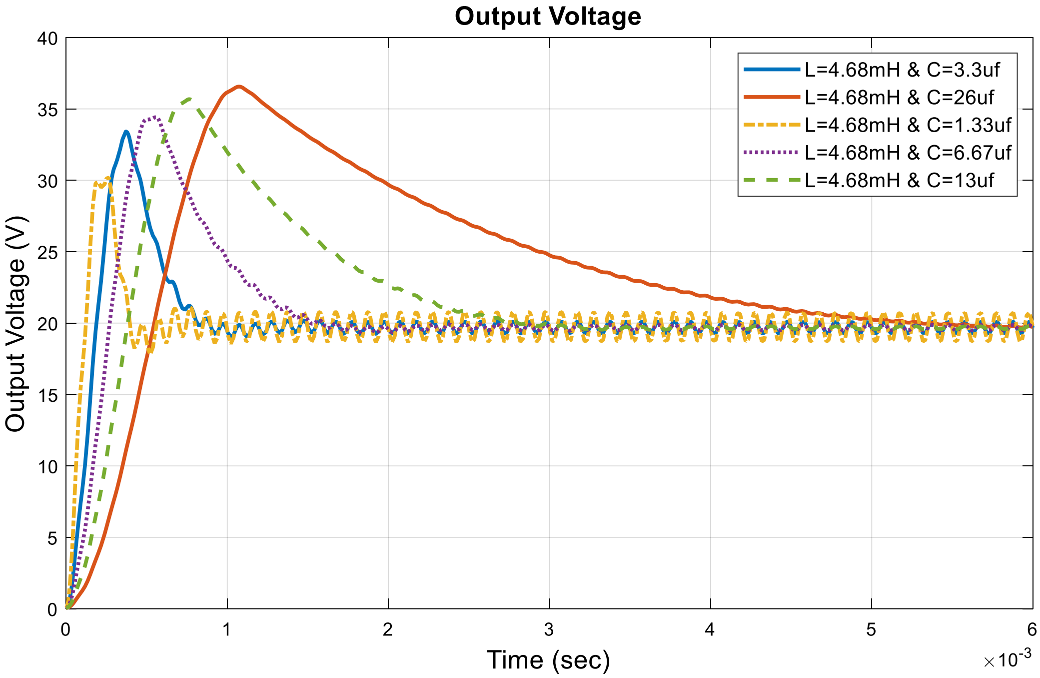

Figure 1.4: Output Response of Buck Converter

Figure 1.3 represents the input signal & gate pulse and Figure 1.4 shows the output for a Buck Converter. First one is the input signal (40V DC), second one is the gate pulse generated by built-in Pulse Generator and the last one is the output waveform - generated by changing the capacitance. There are different values of delay time, rise time, peak time and setting time is drawn here for different capacitor values. The lowest setting time is taken by C= 1.33µF and the highest delay time and rise time is taken by C= 13µF.

❖ Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load).

- The output voltage of a boost converter is always greater than the input voltage.
- During the ON period (T_{on}), i_L increases from I_{Lmin} to I_{Lmax}, thus increasing the magnetic energy stored in inductance L.
- When the switch is opened, current flows through the parallel combination of the load and C. Since, the current is forced against a higher voltage, the rate of change of current is negative. It decreases from I_{Lmax} to I_{Lmin} in the OFF period. The energy stored in the inductance and the energy supplied by the low voltage source are given to the load.

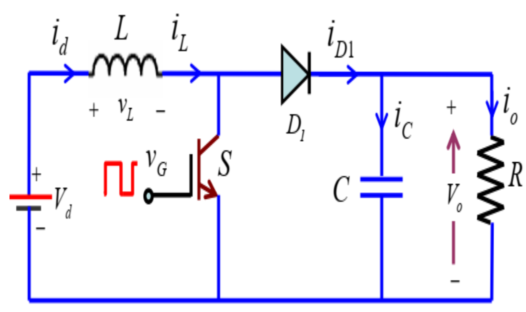

Figure. 1.5: Boost converter

Design parameters for the Boost converter:

Input Voltage ($V_{in\,(dc)}$) = 20 V	Switching Frequency, f= 10kHz
Output Voltage ($V_{o\,(avg)}$) = 40 V	Voltage ripple ($\frac{\Delta V_o}{V_o}$) = 5%, 10%, 1%, 0.5%, 2%
Duty Cycle, D = 1- V_{in}/V_o = 1 - 20 / 40 = 0.5	Current ripple (ΔI) = 5%
Load, R = 150 Ω	
$\boldsymbol{L_{min} = \frac{D(1-D^2)R}{2f} \approx 1.25\,mH}$	$C = \frac{D}{R(\frac{\Delta V_o}{V_o})f}$ = 6.67, 3.33, 33.3, 66, 16 µF

i) Implementation Diagram:

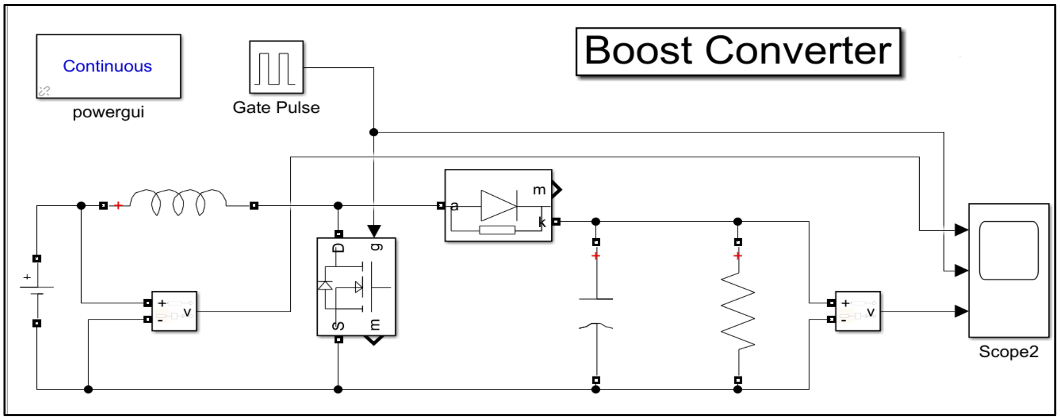

Figure 1.6: Boost Converter

ii) Result:

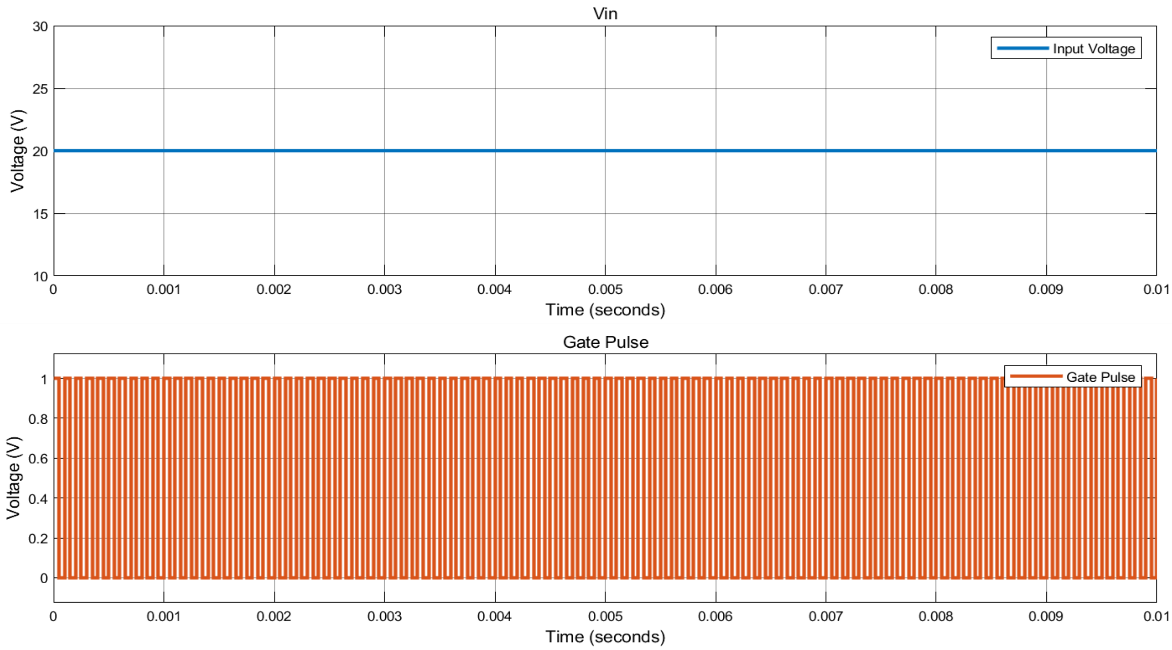

Figure 1.7: Input signal, Gate Pulse

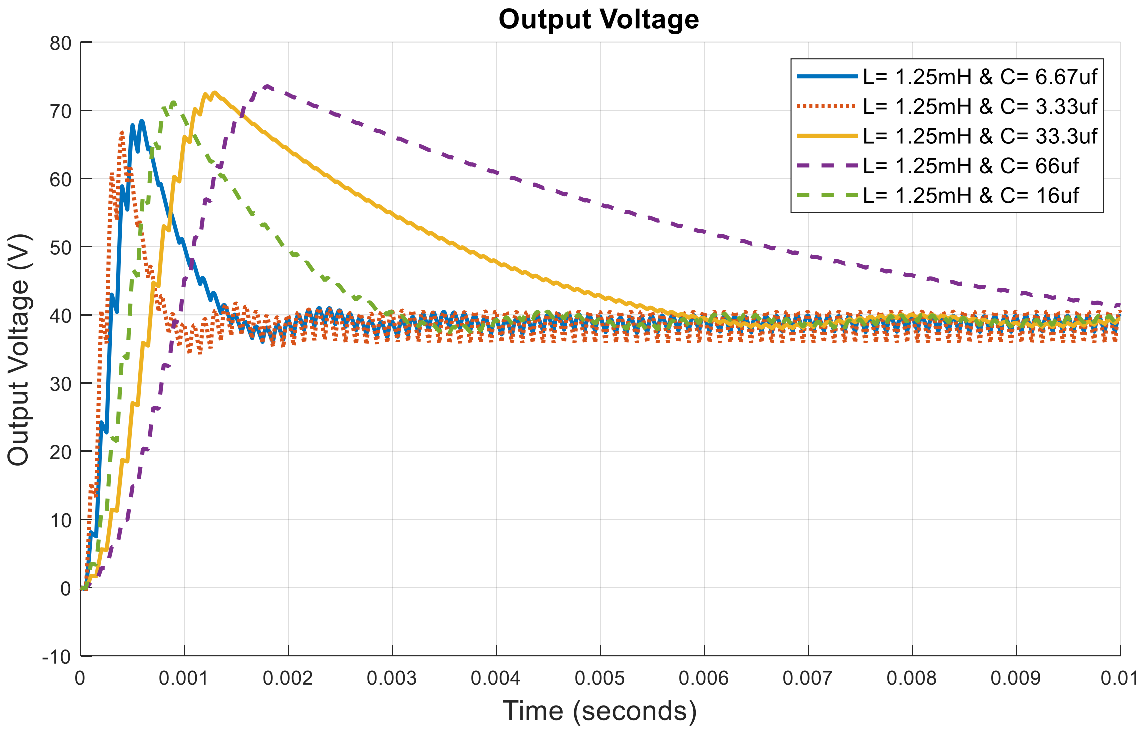

Figure 1.8: Output Response of Boost Converter

Figure 1.7 represents the input signal & gate pulse and Figure 1.8 represents the output for a Boost Converter. The input signal is 20V DC, the gate pulse is generated by built-in Pulse Generator and the output waveform is generated by changing the capacitance. There are different values of delay time, rise time, peak time and setting time is drawn here for different capacitor values. The lowest setting time is taken by C= 3.33μF and the highest delay time and rise time is taken by C= 66μF.

❖ Buck-Boost Converter

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude.

- The main application of a buck-boost converter is in regulated dc power supplies, where a negative polarity output may be desired with respect to the common terminal of the input voltage, and the output voltage can be either higher or lower than the input voltage.
- When the switch is ON, the input provides energy to the inductor and the diode is reverse biased. When the switch is OFF, the energy stored in the inductor is transferred to the output. No energy is supplied by the input during this interval.

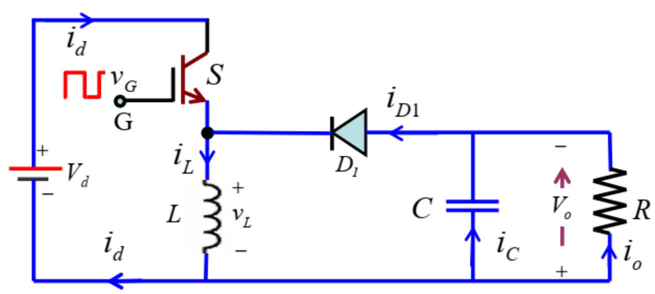

Figure. 1.9: Buck Boost converter

Design parameters for the Buck Boost converter:

Input Voltage ($V_{in\,(dc)}$) = 20 V	Switching Frequency, f= 10kHz
Output Voltage ($V_{o\,(avg)}$) = -10 V	Voltage ripple ($\frac{\Delta V_o}{V_o}$) = 5%, 10%, 1%, 0.5%, 2%
Duty Cycle, D = 0.3333	Current ripple (ΔI) = 5%
Load, R = 150 Ω	
$\boldsymbol{L_{min} = \frac{(1-D^2)R}{2f} \approx 4.12\ mH}$	$C = \frac{D}{R(\frac{\Delta V_o}{V_o})f}$ = 4.4, 2.2, 22, 44, 11 μF

i) Implementation Diagram:

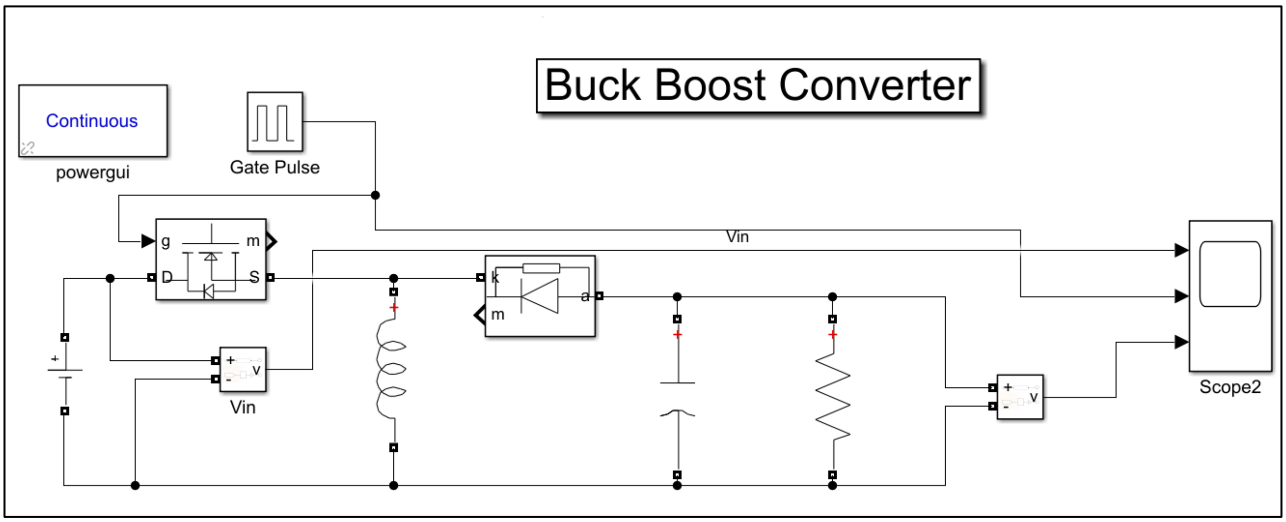

Figure 1.10: Buck-Boost Converter

ii) Result:

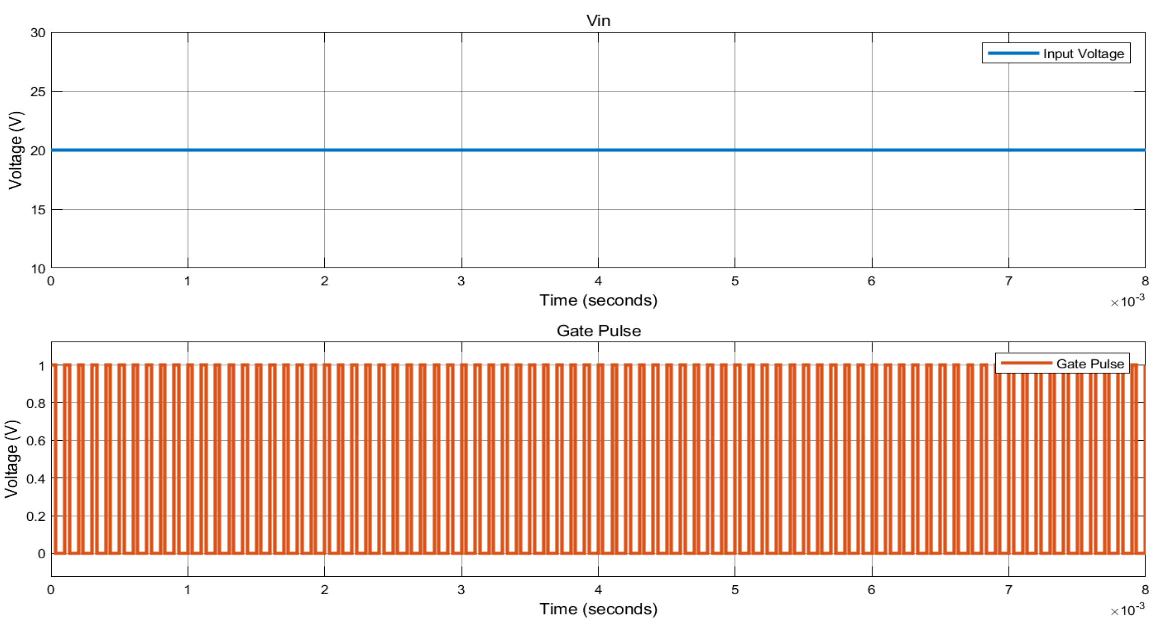

Figure 1.11: Input & Gate Pulse

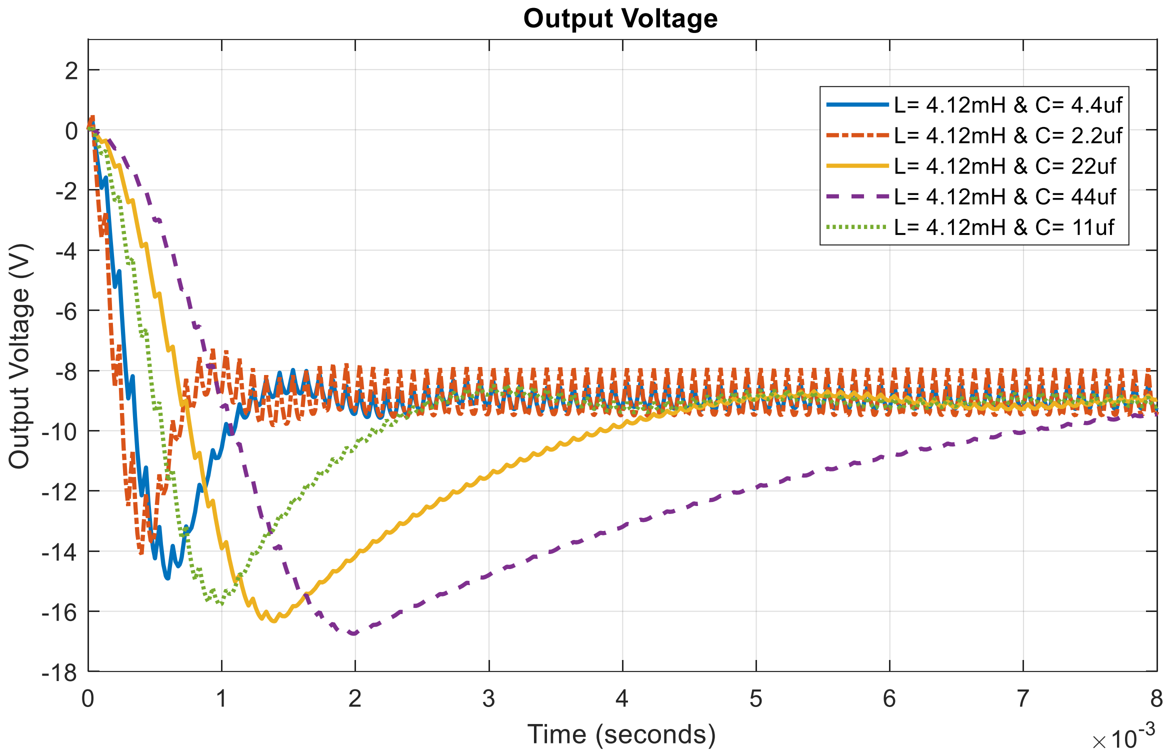

Figure 1.12: Output Response of Buck Boost Converter

Figure 1.11 represents the input signal & gate pulse and Figure 1.12 shows the output for a Buck-Boost Converter. First one is the input signal (20V DC), second one is the gate pulse generated by built-in Pulse Generator and the last one is the output waveform - generated by changing the capacitance. There are different values of delay time, rise time, peak time and setting time is drawn here for different capacitor values. The lowest setting time is taken by C= 2.2μF and the highest delay time and rise time is taken by C= 44μF.

Discussion: In this experiment, DC/DC Converter (Buck, Boost, Buck-Boost) circuits was designed without any feedback component to learn about the basic functionality and characteristics of the converter. The input, output wave-forms, gate pulses was observed in scope for specific input-output voltage. Output voltage was observed by changing the capacitor value (basically output ripple). Capacitor value is changed by using theoretical equation and observed the output voltage each time. Output voltage ripple is decreased by increasing capacitance but mean while the setting time is increased. So, we should have to select an appropriate value of capacitor & inductor to get best conversion by using trade-off technique among steady state error, setting time and others parameter. Thus, the experiment was successfully done.

Experiment No: Extra- 02

Experiment Name: Simulation and Analysis of Close Loop Buck, Boost and Buck-Boost Converter using PID Controller.

Objectives:
The purpose of this experiment is to:
1. Demonstrate the operations and characteristics of DC-DC converter with PID Controller.
2. Design different types of switching converter - Buck, Boost and Buck-Boost for specific input-output voltage with a PID controller.
3. Observe the input-output waveform of the Converters using MATLAB Simulink.

Theory:
Dc-dc converters are power electronic circuits that convert a dc voltage to a different dc voltage level, often providing a regulated output. Most commonly used switch mode regulators are–Buck Converter, Boost Converter, Buck-Boost Converter and Ćuk Converter. The converter circuits can be open loop (i.e., the output has no effect on the control action) or close loop (i.e., output of a system is feedback and compared with the desired output/reference response). A PID controller is an instrument used in industrial control applications to regulate temperature, flow, pressure, speed and other process variables. PID (proportional integral derivative) controllers use a control loop feedback mechanism to control process variables and are the most accurate and stable controller. All of that converter is simulated here with proper circuit diagram, input-output waveform.

Required Software: MATLAB/Simulink

Experimental Analysis:

❖ **Buck Converter**

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while drawing less average current) from its input (supply) to its output (load).

- When the switch S is ON, the diode D1 is OFF as it is reverse biased. The current flows through the inductor to the load.
- When the switch is OFF, the diode becomes forward biased because of the negative inductor voltage. Diode D1 provides path for the load current to flow when the switch S is OFF and improves the load current waveform. Furthermore, by maintaining the continuity of the load current at turn-off, it prevents transient voltage from appearing across the switch, due to sudden change of the load current.

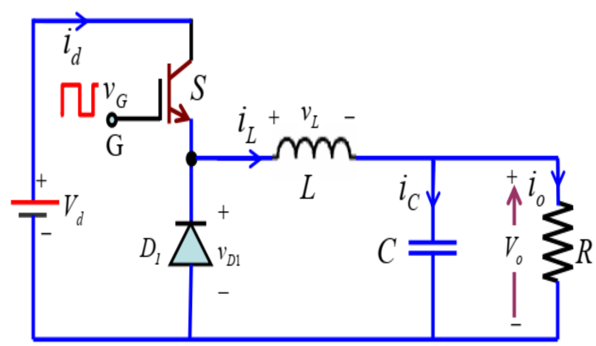

Figure. 2.1: Buck converter

The gate pulse will generate by PID controller by comparing the output and the reference value at every instant of time.

Design parameters for the Buck converter:

Input Voltage ($V_{in\,(dc)}$) = 30 V	Switching Frequency, f= 40kHz
Output Voltage ($V_{o\,(avg)}$) = 15 V	Voltage Ripple ($\frac{\Delta V_o}{V_o}$) = 5%
Duty Cycle, D = V_o/V_{in} = 15 / 30 = 0.5	Load, R = 8 Ω
$\boldsymbol{L_{min} = \frac{(1-D)R}{2f} = 50\ \mu H\ \approx 85.95\ \mu H}$	$C = \frac{1-D}{8L(\frac{\Delta V_o}{V_o})f^2} = 9.09\ \mu F\ \approx 12.5\ \mu F$

i) Implementation Diagram:

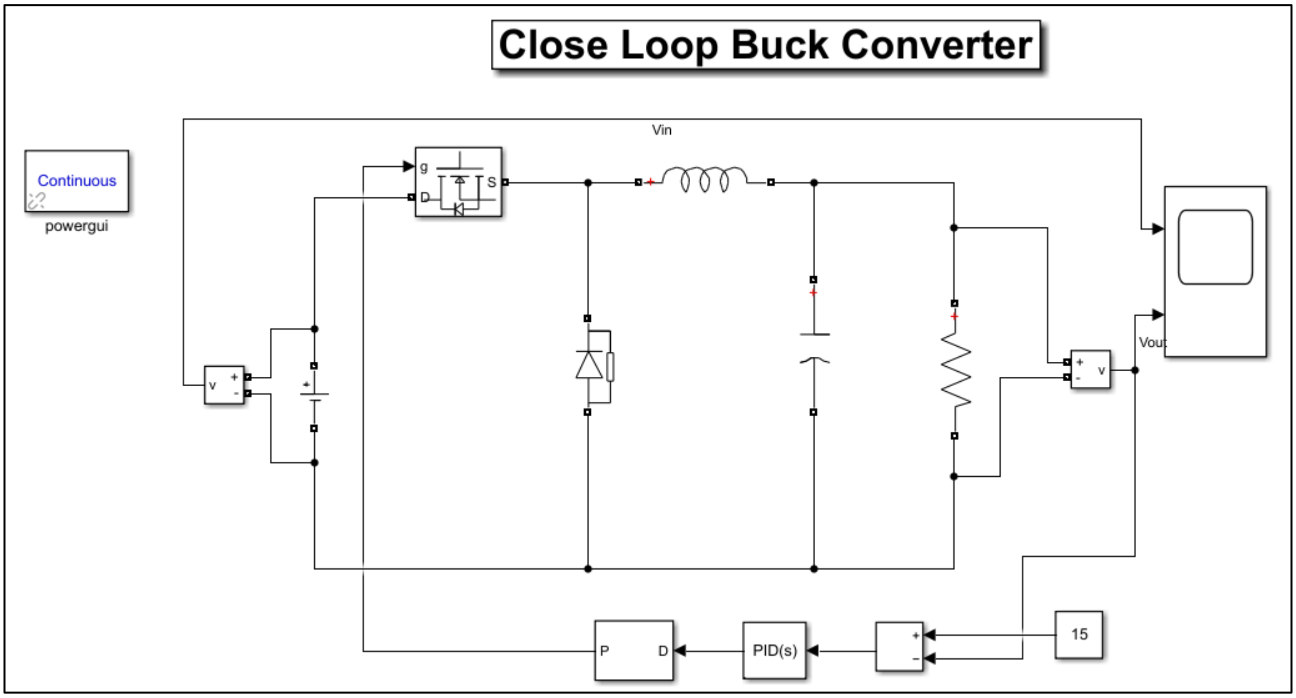

Figure 2.2: Close-Loop Buck Converter

ii) Result:

Figure 2.3 represents the input and output for a Close loop Buck Converter. First one is the input signal (30V DC), and the last one is the output waveform. A PID controller is used here to generate gate pulse which is generating pulse by comparing with the reference voltage (15V) at every instant of time.

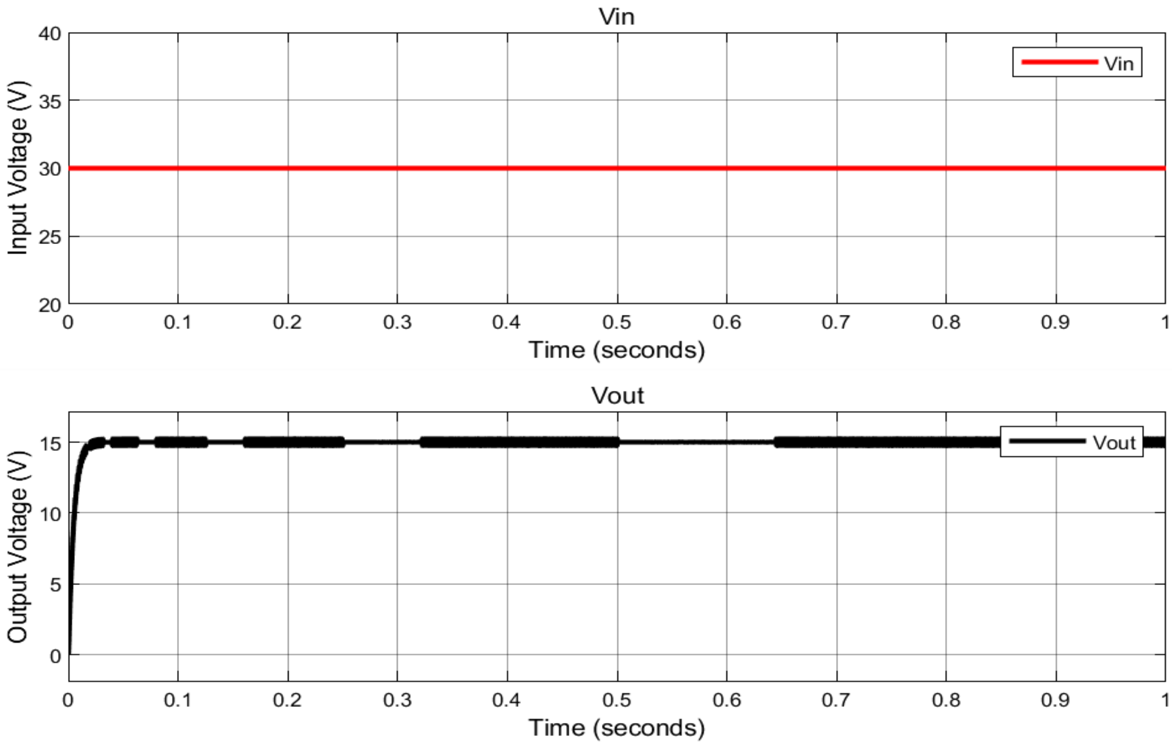

Figure 2.3: Input & Output Response

❖ Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load).

- The output voltage of a boost converter is always greater than the input voltage.
- During the ON period (T_{on}), i_L increases from I_{Lmin} to I_{Lmax}, thus increasing the magnetic energy stored in inductance L.
- When the switch is opened, current flows through the parallel combination of the load and C. Since, the current is forced against a higher voltage, the rate of change of current is negative. It decreases from I_{Lmax} to I_{Lmin} in the OFF period. The energy stored in the inductance and the energy supplied by the low voltage source are given to the load.

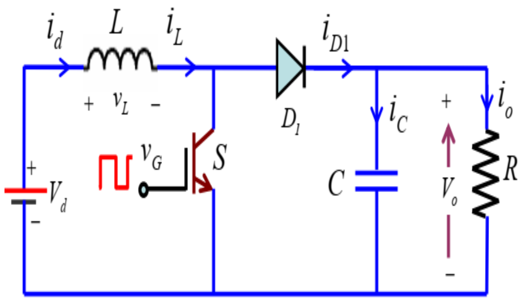

Figure. 2.4: Boost converter

The gate pulse will generate by PID controller by comparing the output and the reference value at every instant of time.

Design parameters for the Boost converter:

Input Voltage ($V_{in\,(dc)}$) = 10 V	Switching Frequency, f= 20kHz
Output Voltage ($V_{o\,(avg)}$) = 20 V	Voltage ripple ($\frac{\Delta V_o}{V_o}$) = 5%

Duty Cycle, $D = 1 - V_{in}/V_o = 1 - 10 / 20 = 0.5$	Load, R = 3.2 kΩ
$L_{min} = \dfrac{D(1-D^2)R}{2f} \approx 25\ mH$	$C = \dfrac{D}{R(\frac{\Delta V_o}{V_o})f} = \approx 1\ \mu F$

ii) Implementation Diagram:

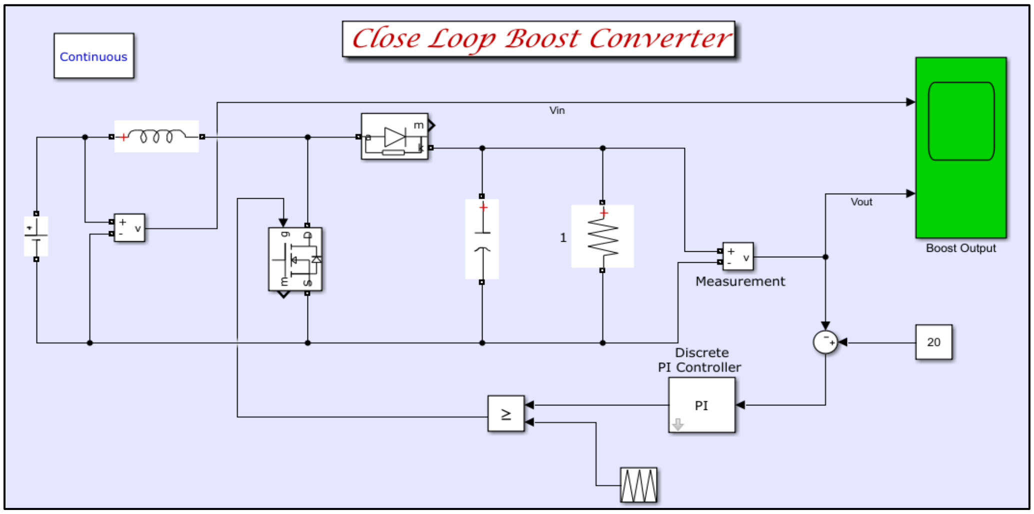

Figure 2.5: Close Loop Boost Converter

ii) Result:

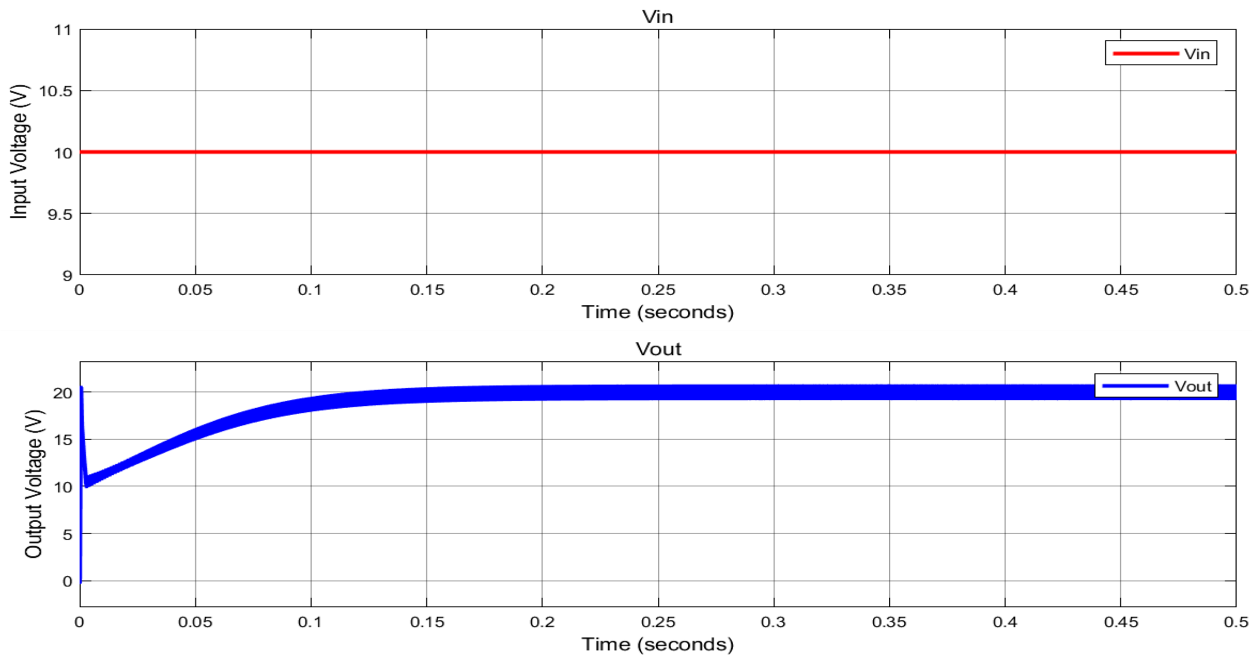

Figure 2.6: Input & Output Response

Figure 2.6 represents the input and output for a close loop Boost Converter. First one is the input signal (10V DC) and the last one is the output waveform. A PID controller is used here to generate gate pulse which is generating pulse by comparing with the reference voltage (20V) at every instant of time.

❖ **Buck-Boost Converter**

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude.

- The main application of a buck-boost converter is in regulated dc power supplies, where a negative polarity output may be desired with respect to the common terminal of the input voltage, and the output voltage can be either higher or lower than the input voltage.
- When the switch is ON, the input provides energy to the inductor and the diode is reverse biased. When the switch is OFF, the energy stored in the inductor is transferred to the output. No energy is supplied by the input during this interval.

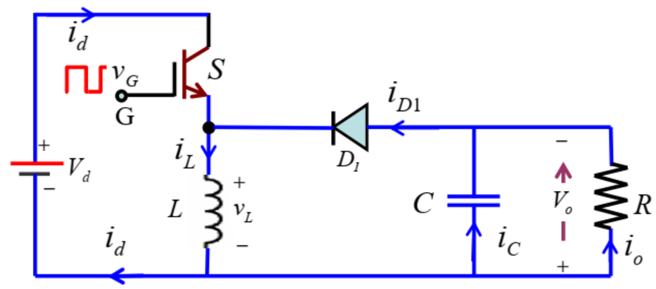

Figure. 2.7: Buck Boost converter

The gate pulse will generate by PID controller by comparing the output and the reference value at every instant of time.

Design parameters for the Buck Boost converter:

Input Voltage ($V_{in\ (dc)}$) = 12 V	Switching Frequency, f= 5kHz
Output Voltage ($V_{o\ (avg)}$) = -4 V	Voltage ripple ($\frac{\Delta V_o}{V_o}$) = 5%
Duty Cycle, D = $\frac{V_o}{V_o - V_{in}}$ = 0.25	Load, R = 3 Ω
$L_{min} = \frac{(1-D^2)R}{2f} = 0.28\ mH \approx 1.5\ mH$	$C = \frac{D}{R(\frac{\Delta V_o}{V_o})f}$ =333.33 μF ≈ 250 μF

i) Implementation Diagram:

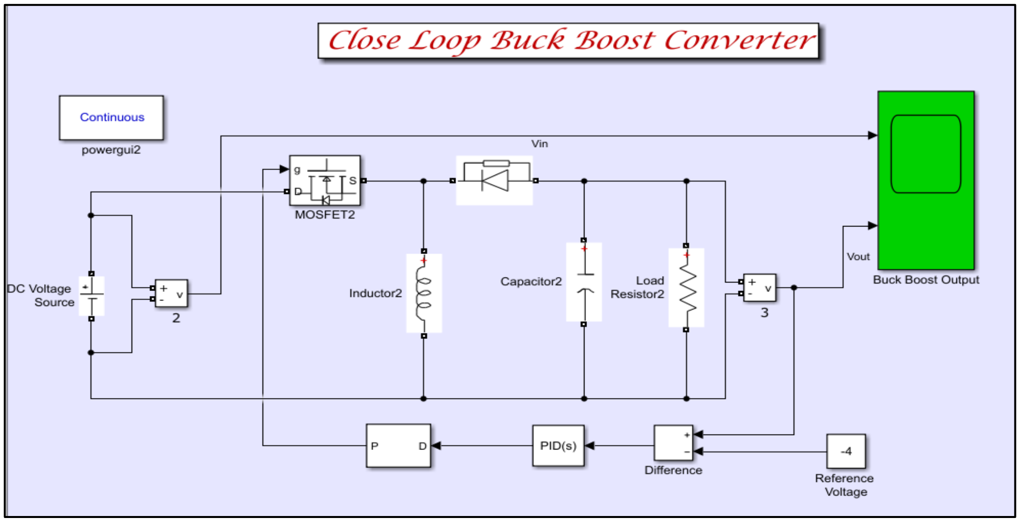

Figure 2.8: Close Loop Buck-Boost Converter

ii) Result:

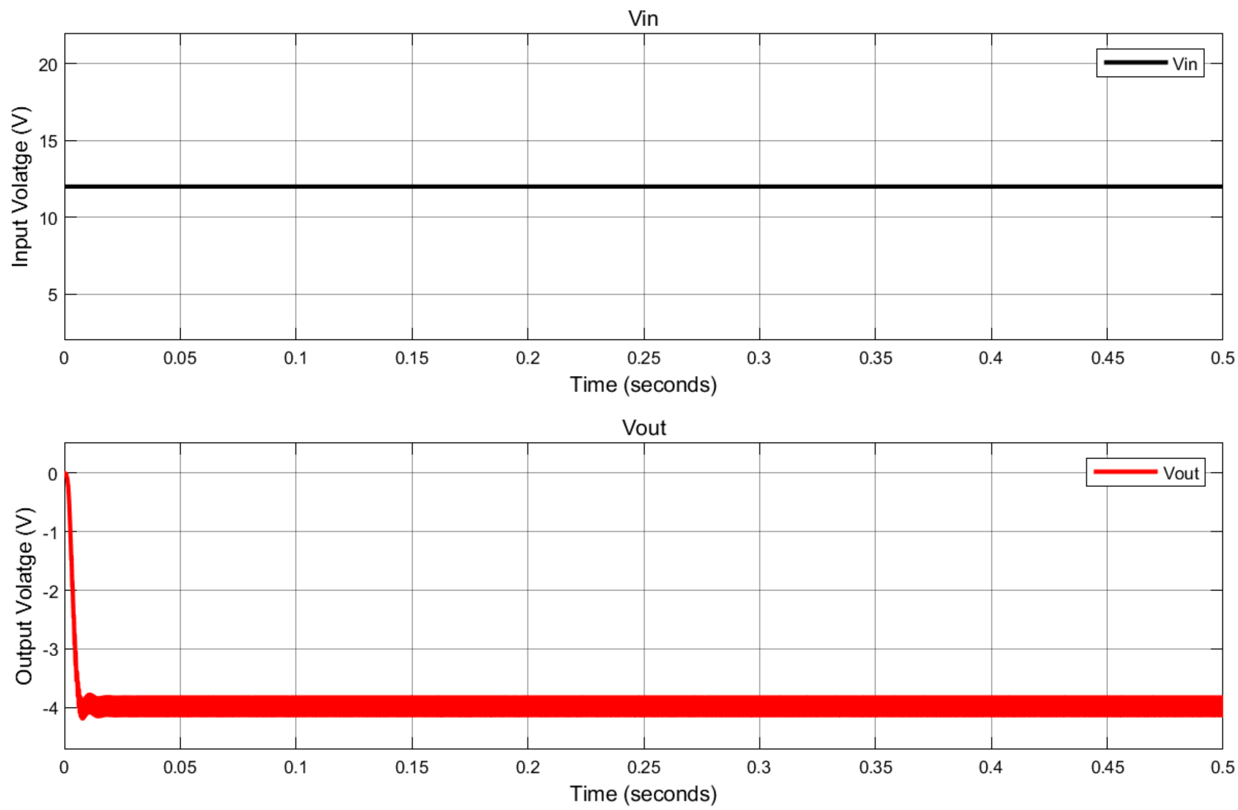

Figure 2.9: Input & Output Response

Figure 2.9 represents the input and output for a close loop Buck-Boost Converter. First one is the input signal (12V DC) and the last one is the output waveform. A PID controller is used here to generate gate pulse which is generating pulse by comparing with the reference voltage (-4V) at every instant of time.

Discussion: In this experiment, DC/DC Converter (Buck, Boost, Buck-Boost) circuits was designed with feedback component to learn about the basic functionality and characteristics of the controlled converter. The input & output wave-forms was observed in scope for specific input-output voltage. Output voltage is observed by tuning the PID's parameters. The controller receives the difference between the reference set point and the measured output (known as error) and generates a control action to make the error to zero. So, everybody should have to select an appropriate value of P, I & D to get best conversion. Thus, the experiment was successfully done.