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Question

A boost converter has the following specifications:

$$V_{in} = 12V, V_{out} = 24V, \text{Load} = 100 \text{ ohms}, \text{Fs} = 20\text{kHz}, L = 10^{-3}\text{H}, \text{Resistance} = 0.1\text{ohm},$$

$$C_o = 12.5^{-6}\text{F}$$

The input voltage may vary from 8V to 16V, whereas the load resistance ranges from 50 to 200 ohms.

1 Part A

Design the PI controller parameters for the closed-loop system such that the desired output voltage is obtained while satisfying the following criteria:

- Output voltage lies in the range of 23.5 volts to 24.5 volts
- Settling time < 50ms
- Maximum overshoot < 26.4 Volts

1.1 PI controller

In the PI controller, the actuating signal is directly proportional to the error signal added with the integral of the error signal. It also reduces steady-state error without affecting of stability of the system, especially since K_p is large.

$$\mathbf{u_a(t) = \alpha\ e(t) + \int e(t)d(t)}$$

$$\mathbf{u_a(t) = K_p e(t) + K_I \int e(t)d(t)}$$

Taking laplace on both sides

$$\mathbf{U_a(s) = K_p \times E(s) + \frac{K_I}{s} \times E(s)}$$

$$\mathbf{U_a(s) = E(s)\left[K_P + \frac{K_I}{s}\right]}$$

$$U_a(s) = E(s)K_P\left[1 + \frac{K_I}{sK_P}\right]$$

$$U_a(s) = E(s)K_P\left[1 + \frac{1}{\tau_I s}\right]$$

$$\text{as } \tau_I = \frac{K_P}{K_I} = \text{Integral Time}$$

$$\boxed{\frac{U_a(s)}{E(s)} = K_P\left[1 + \frac{1}{\tau_I s}\right]}$$

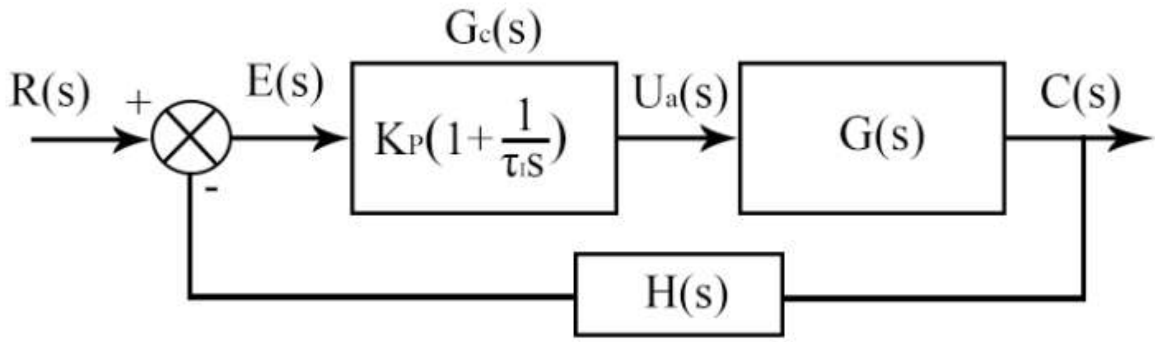


Figure 1 Proportional Integral Controller

1.2 PI controller for boost converter

Boost converters are one of the most fundamental switch-mode converter types. Its name indicates its primary purpose, increasing the voltage from an input source. This switch consists of four parts: an inductor, a capacitor, a diode, and a semiconductor switch. DC sources such as batteries, solar panels, rectifiers, and DC generators are suitable. "DC to DC conversion" refers to the process of converting one direct current (DC) voltage to another direct current (DC) voltage. So, when the controller's output voltage is with the PI controller, the load or desired set point abruptly changes, and the PI regulator moves the boost converter's output much closer to the working point. Figure 2 shows the boost converter circuit with the PI controller.

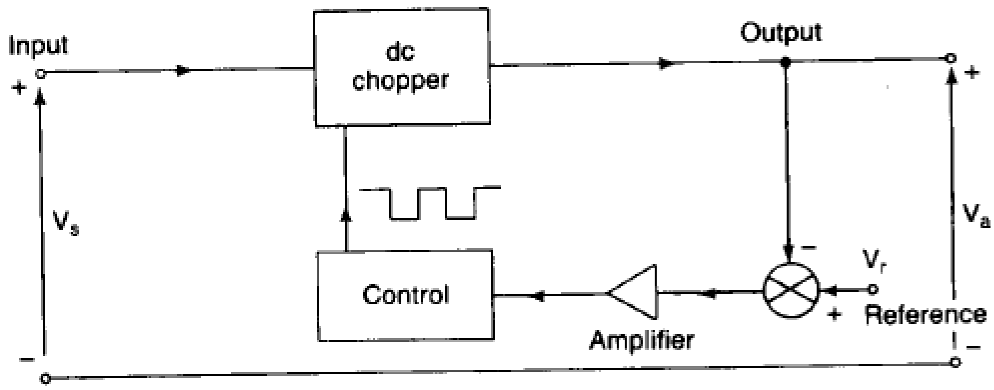


Figure 2 Schematic for PI control for boost converter

1.3 Hands-on calculation

The hands-on calculation I wrote is given:

$V_{in} = 12V$

$V_o = 24V$

$R = 100\Omega$

$F_s = 20KHz$

$L = 10^{-3}H$

$C_o = 12.5 \times 10^{-6}$

$$\Delta L = \frac{12(24-12)}{(20\times10^{3})(10\times10^{-3})\times 24}$$

$$\boxed{\Delta L = 0.03A}$$

For duty cycle - $K =$

$$V_{in} = V_{out}(1-K)$$

$$\frac{12}{24} = 1-K$$

$$\boxed{K = 0.5}$$

I_s = Peak inductor current

$$I_s = 0.16/1-0.5$$

$$\boxed{I_s = 0.32A}$$

0.16: load current

$$I_2 = I_s + \frac{\Delta I}{2}$$

$$I_2 = I_s + \frac{\Delta I}{2}$$

$$I_2 = 0.32 + \frac{0.03}{2}$$

$$\boxed{I_2 = 0.335}$$

$$\Delta V_c = \frac{0.16 \times 0.5}{20000 \times 12.5 \times 10^{-6}}$$

$$\Delta V_c = \frac{0.16 \times 0.5}{0.25}$$

$$\boxed{\Delta V_c = 0.32}$$

1.4 Software simulation

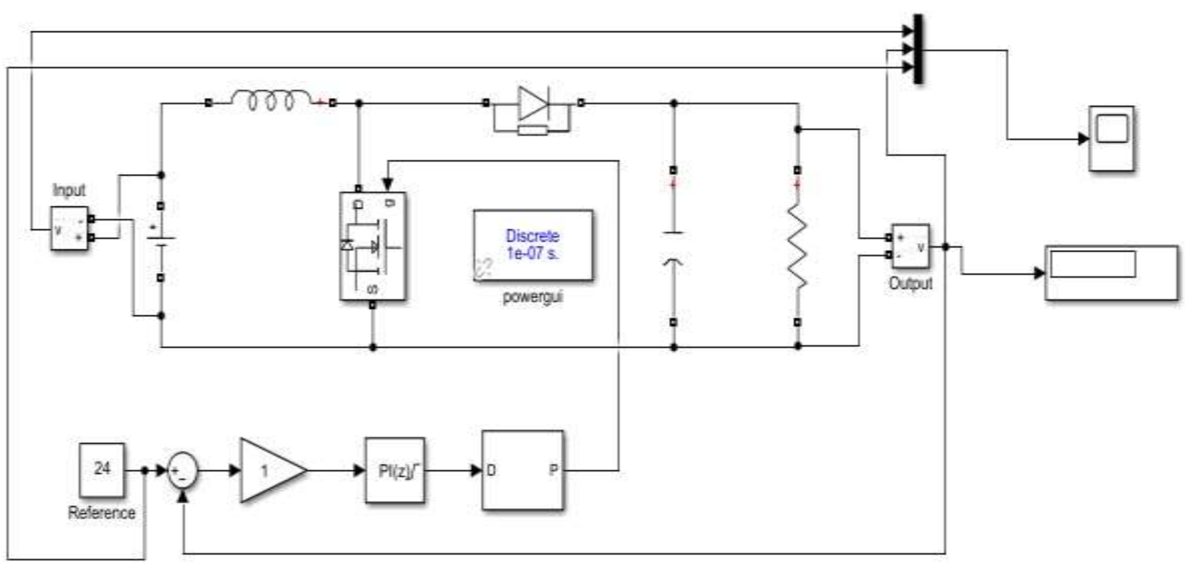


Figure 3 Circuit diagram of the boost converter with PI control

As shown in figure 3, the reference voltage must be set to 24 volts to achieve the desired time response by keeping the voltage below 24.5 volts. The PI control block has been imported from the Simulink library, and here is the gain block to give amplitude to the signal. So, to control voltages, it is necessary to compare the output voltage to the reference voltage. The D to P block (duty cycle determines the percentage of the pulse period that the output) is the PWM generator in which the switching frequency is set to 20kHz under the specifications.

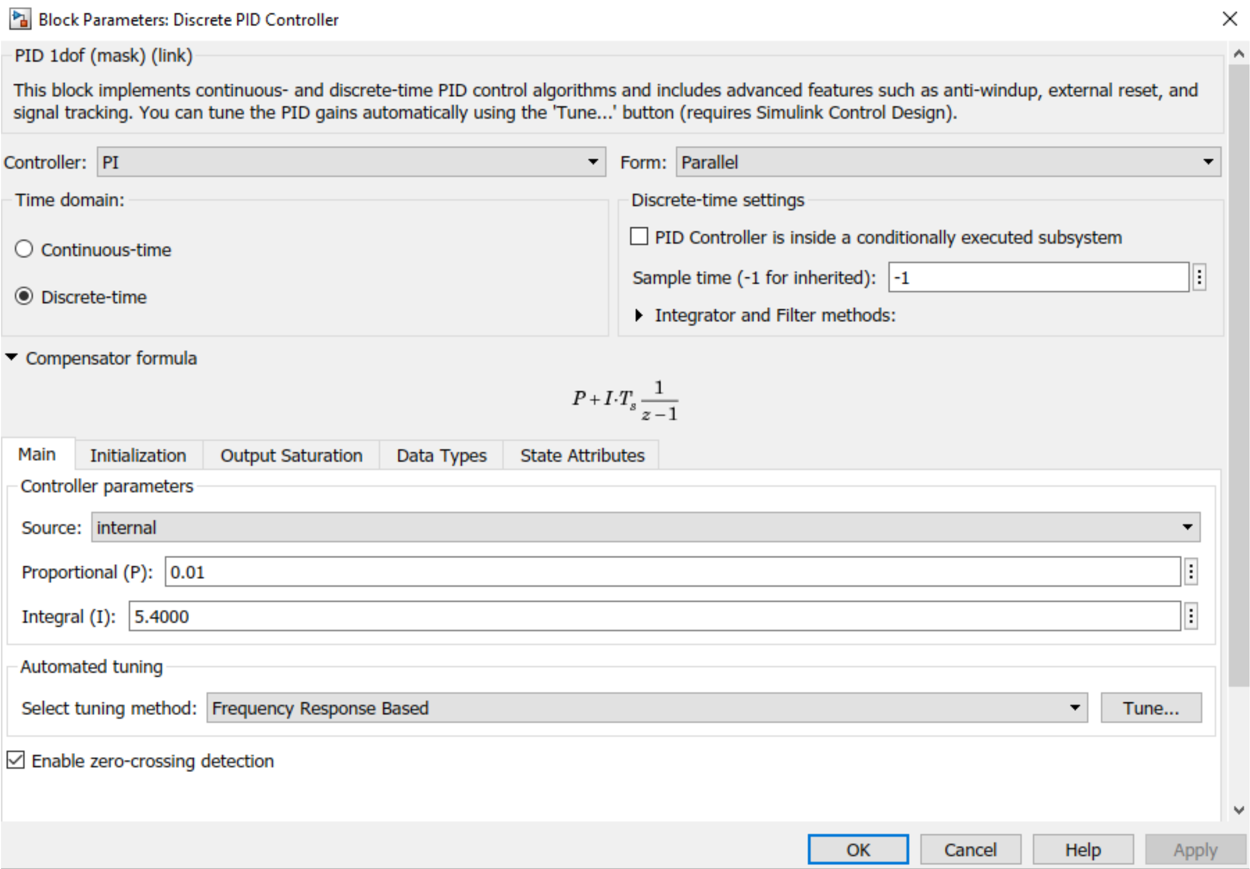


Figure 4 PI controller specification

As seen in figure 4, the proportional gain and the integral gain of the PI block is Proportional is 0.01, and the integral is 5.4, which is achieved by getting the maximum value of proportional, which is K_{max}, and it is the point where maximum overshoots occur. It means the system is unstable, and here the calculation of the proportional controller occurs with the help of Ziegler-Nichols's method. The values can be achieved by entering the values in the following formulas:

$$P = 0.45 * K_{max}$$

$$I = 1.2 * P/0.001$$

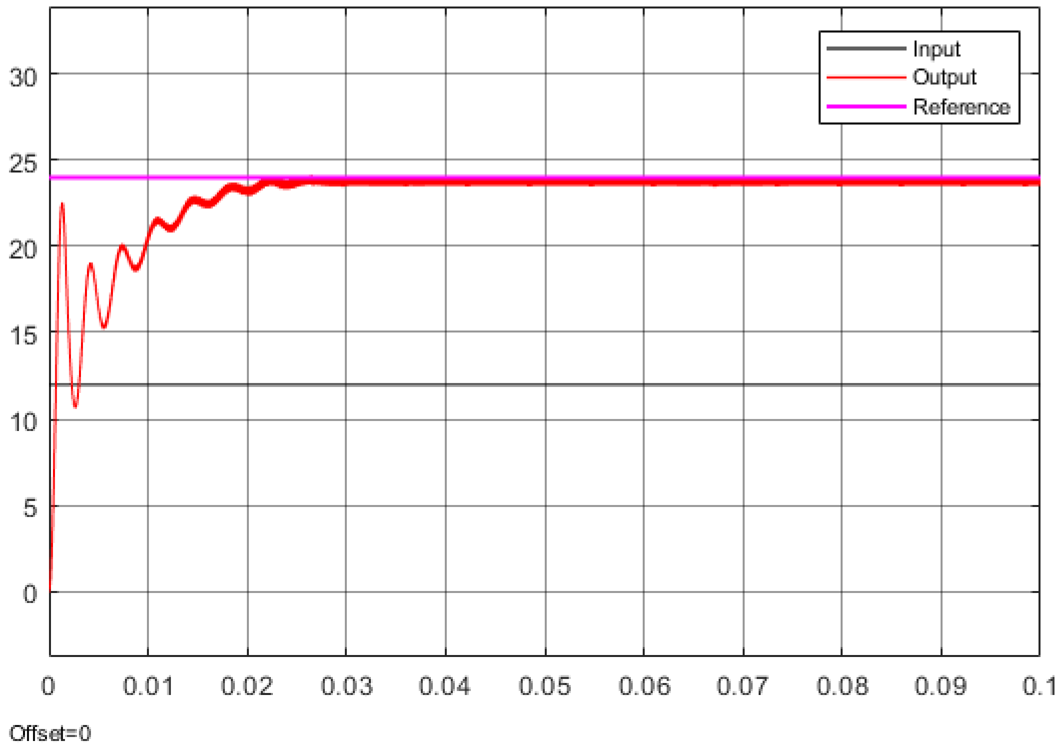


Figure 5 Part A simulation of PI controller

▼ Transitions

High	2.376e+01
Low	1.072e+01
Amplitude	1.304e+01
+ Edges	1
+ Rise Time	10.719 ms
+ Slew Rate	973.037 (/s)
- Edges	0

▼ Overshoots / Undershoots

+ Preshoot	82.407 %
+ Overshoot	2.778 %
+ Undershoot	6.182 %
+ Settling Time	19.991 ms

Figure 6 Overshoot and settling time of the simulation

The percentage overshoot and the settling time is within the range. So, our controller for the boost converter is under the requirements.

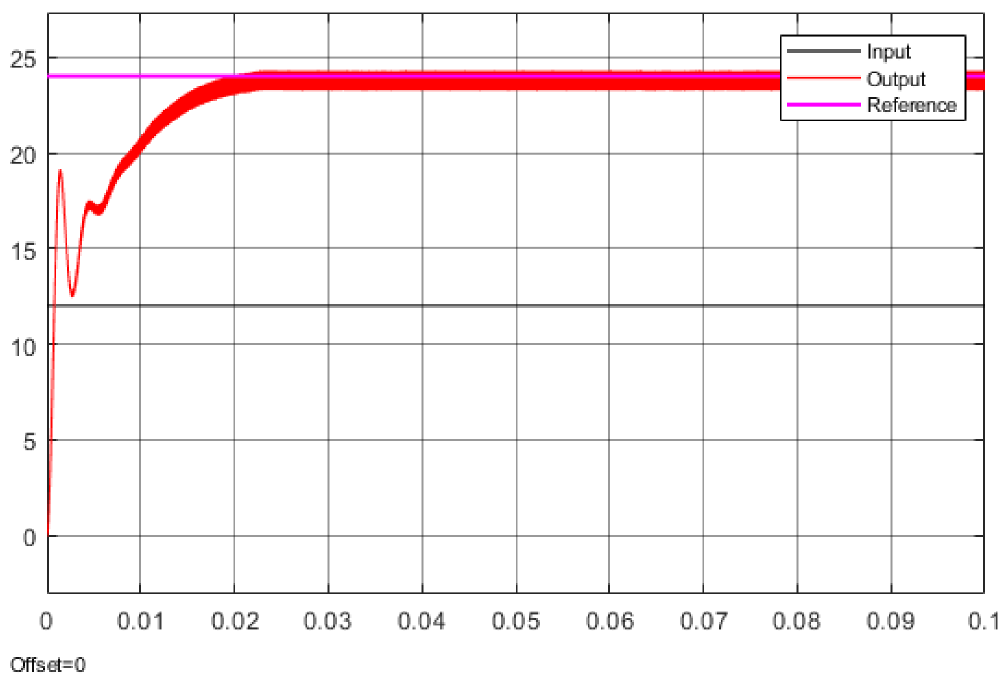
2 Part B

To verify the performance, show the steady-state output voltage, settling time and overshoot at the startup for the following cases:

1. $\mathrm{Vin} = 12\mathrm{V}, \mathrm{Load} = 50, 100 \text{ and } 200 \text{ ohms}$
2. $\mathrm{Vin} = 8\mathrm{V}, \mathrm{Load} = 50, 100 \text{ and } 200 \text{ ohms}$
3. $\mathrm{Vin} = 16\mathrm{V}, \mathrm{Load} = 50, 100 \text{ and } 200 \text{ ohms}$
4. $\mathrm{Vin} = 12\mathrm{V}, \mathrm{Load} = 1000 \text{ ohms}$

2.1 Part 1

2.1.1 With 50 ohms



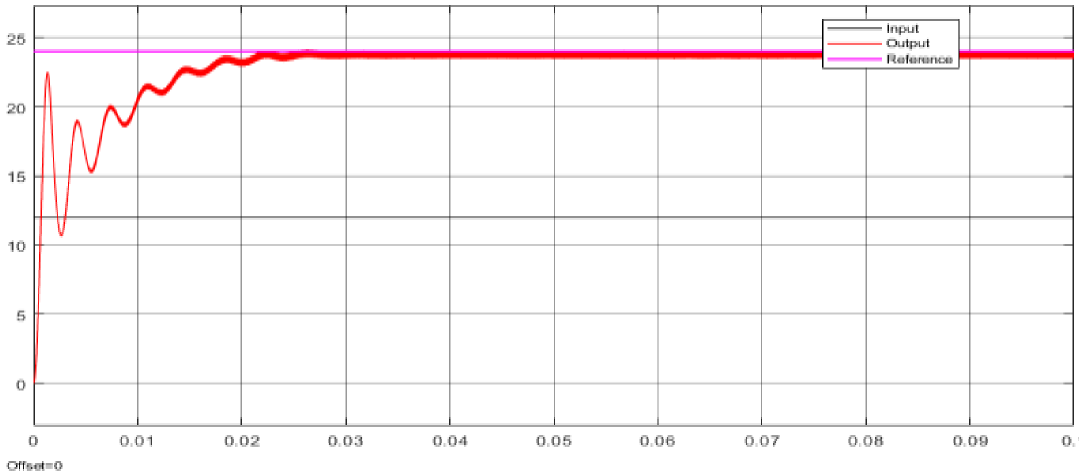
High	2.344e+01
Low	9.979e-02
Amplitude	2.334e+01
+ Edges	1
+ Rise Time	10.208 ms
+ Slew Rate	1.830 (/ms)

▼ Overshoots / Undershoots

+ Preshoot	0.521 %
+ Overshoot	3.646 %
+ Undershoot	5.954 %
+ Settling Time	19.975 ms

Figure 7 Settling time and overshoot with 50 ohms load

2.1.2 With 100 ohms



▼ Transitions

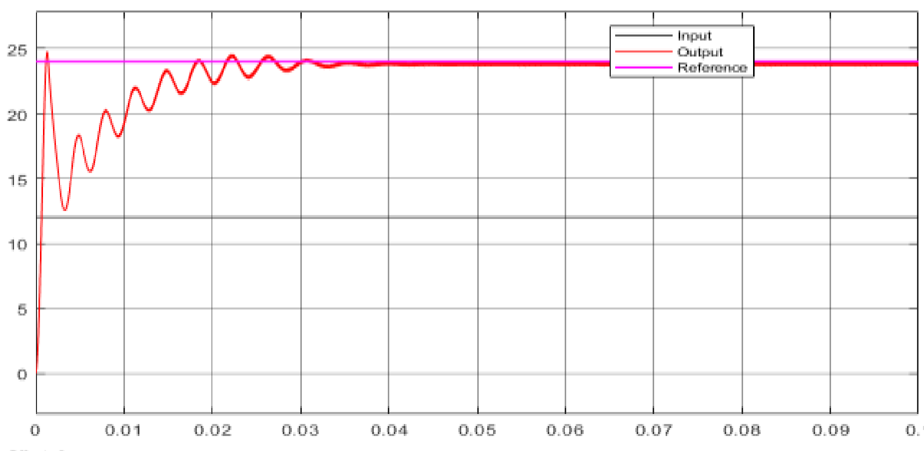
High	2.376e+01
Low	1.072e+01
Amplitude	1.304e+01
+ Edges	1
+ Rise Time	10.719 ms
+ Slew Rate	973.037 (/s)

▼ Overshoots / Undershoots

+ Preshoot	82.407 %
+ Overshoot	2.778 %
+ Undershoot	6.182 %
+ Settling Time	19.991 ms

Figure 8 Settling time and overshoot with 100 ohms load

2.1.3 With 200 ohms



▼ Transitions

High	2.391e+01
Low	1.020e-01
Amplitude	2.380e+01
+ Edges	1
+ Rise Time	734.576 μs
+ Slew Rate	25.923 (/ms)

▼ Overshoots / Undershoots

+ Preshoot	0.521 %
+ Overshoot	3.646 %
+ Undershoot	47.851 %
+ Settling Time	--

Figure 9 Settling time and overshoot with 200 ohms load

2.2 Part 2

2.2.1 With 50 ohms

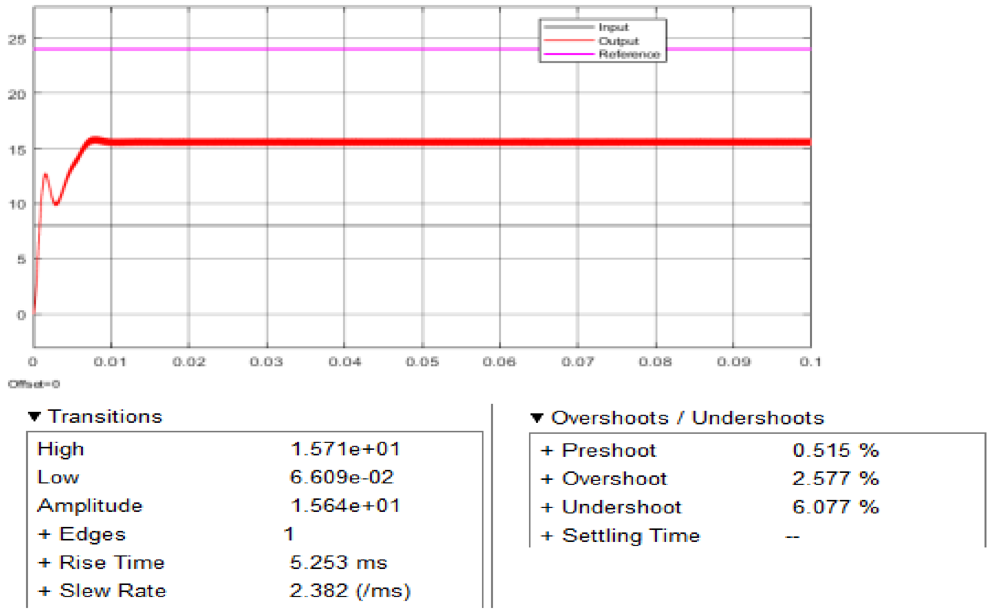


Figure 10 Part 2 settling time and overshoot with 50 ohms load

2.2.2 With 100 ohms

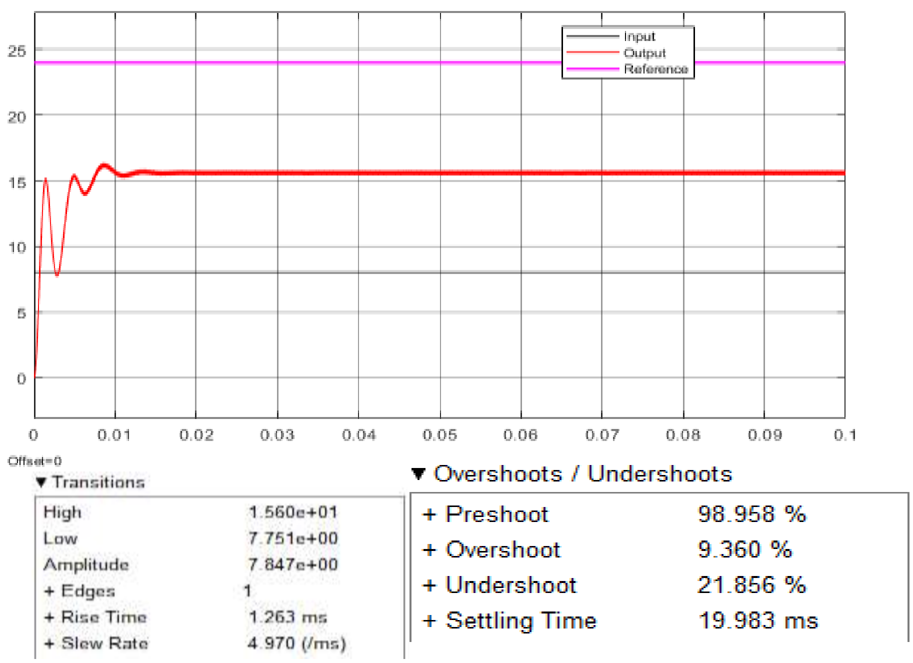
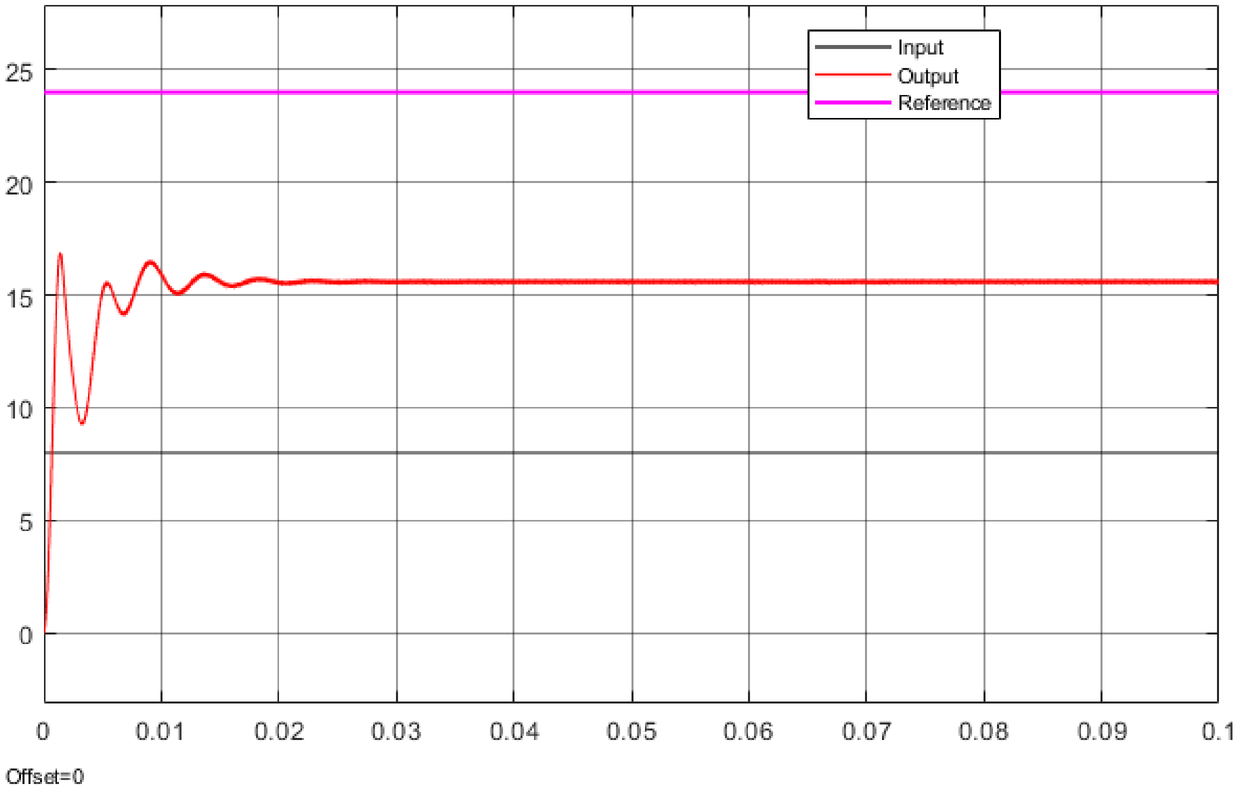


Figure 11 Part 2 settling time and overshoot with 100 ohms load

2.2.3 With 200 ohms



▼ Transitions

High	1.560e+01
Low	6.978e-02
Amplitude	1.553e+01
+ Edges	1
+ Rise Time	755.364 μs
+ Slew Rate	16.453 (/ms)

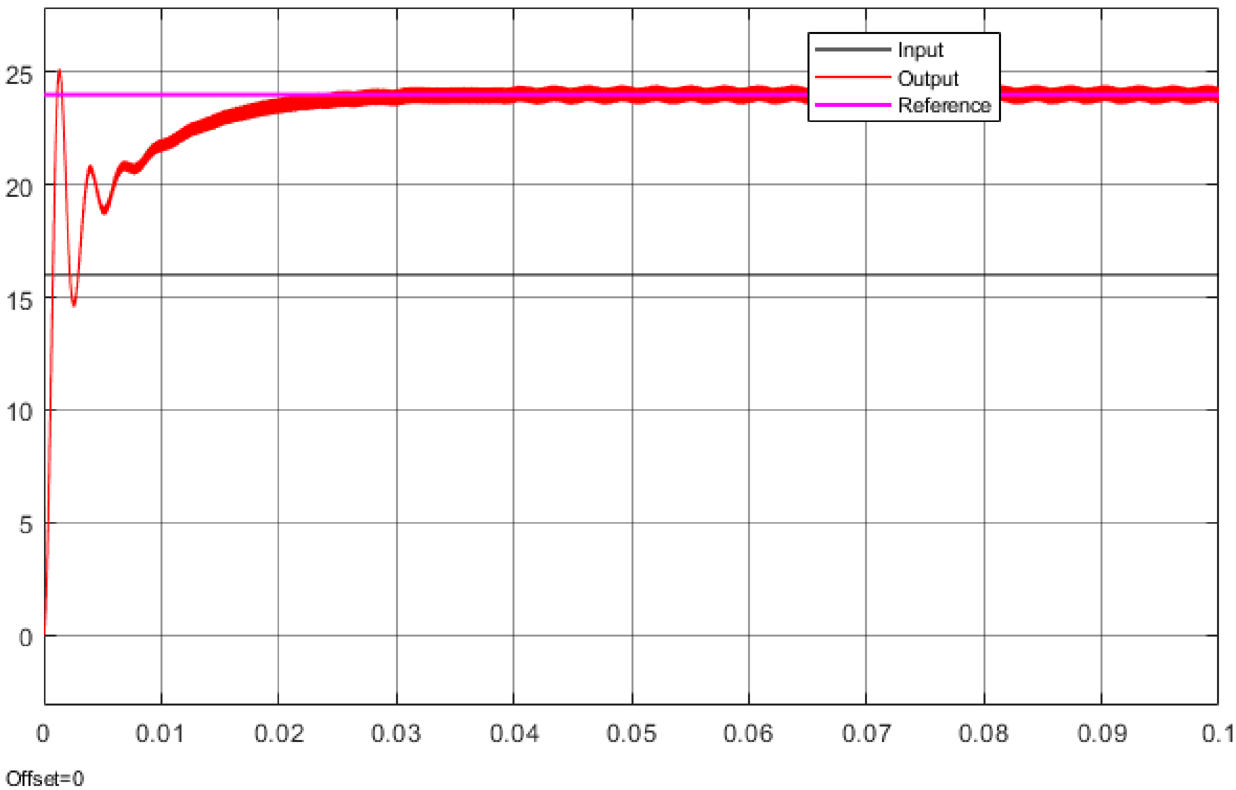
▼ Overshoots / Undershoots

+ Preshoot	0.543 %
+ Overshoot	8.152 %
+ Undershoot	40.949 %
+ Settling Time	13.520 ms

Figure 12 Part 2 settling time and overshoot with 200 ohms load

2.3 Part 3

2.3.1 With 50 ohms



▼ Transitions

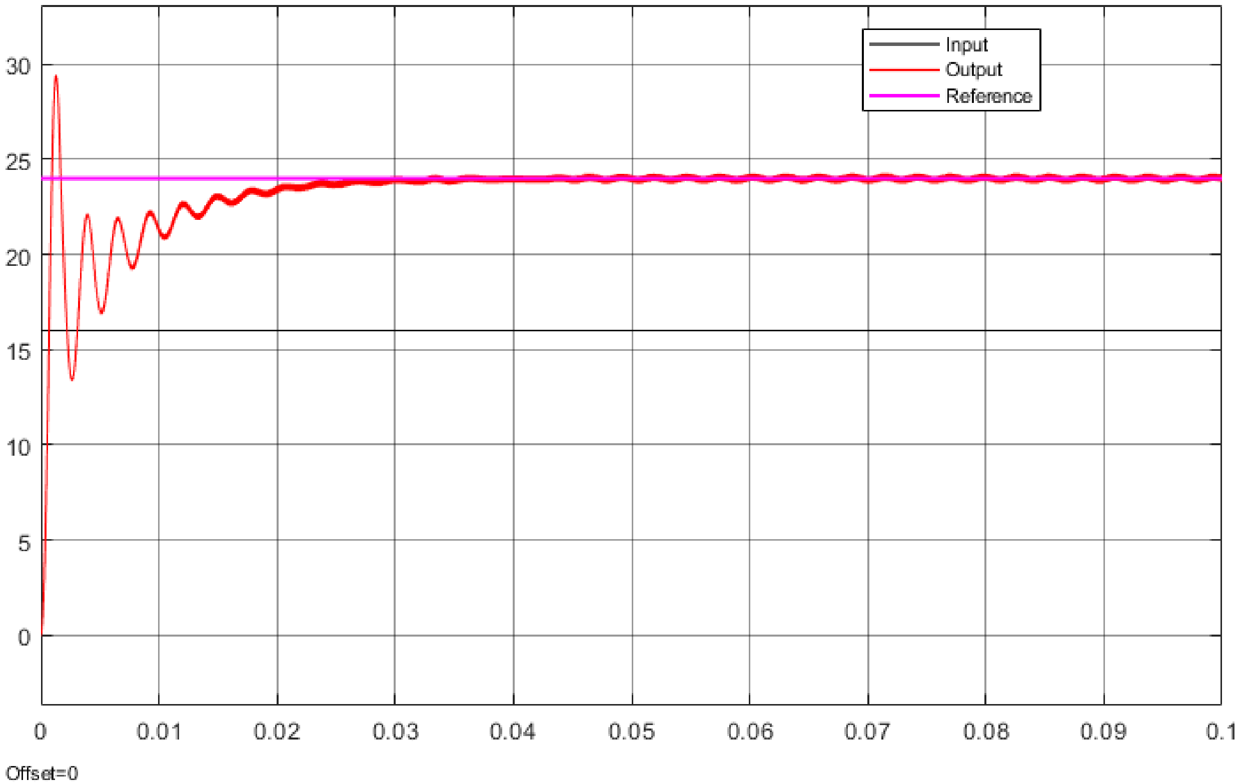
High	2.401e+01
Low	9.677e-02
Amplitude	2.391e+01
+ Edges	1
+ Rise Time	742.637 µs
+ Slew Rate	25.756 (/ms)

▼ Overshoots / Undershoots

+ Preshoot	0.526 %
+ Overshoot	4.737 %
+ Undershoot	39.437 %
+ Settling Time	--

Figure 13 Part 3 settling time and overshoot with 50 ohms load

2.3.2 With 100 ohms



▼ Transitions

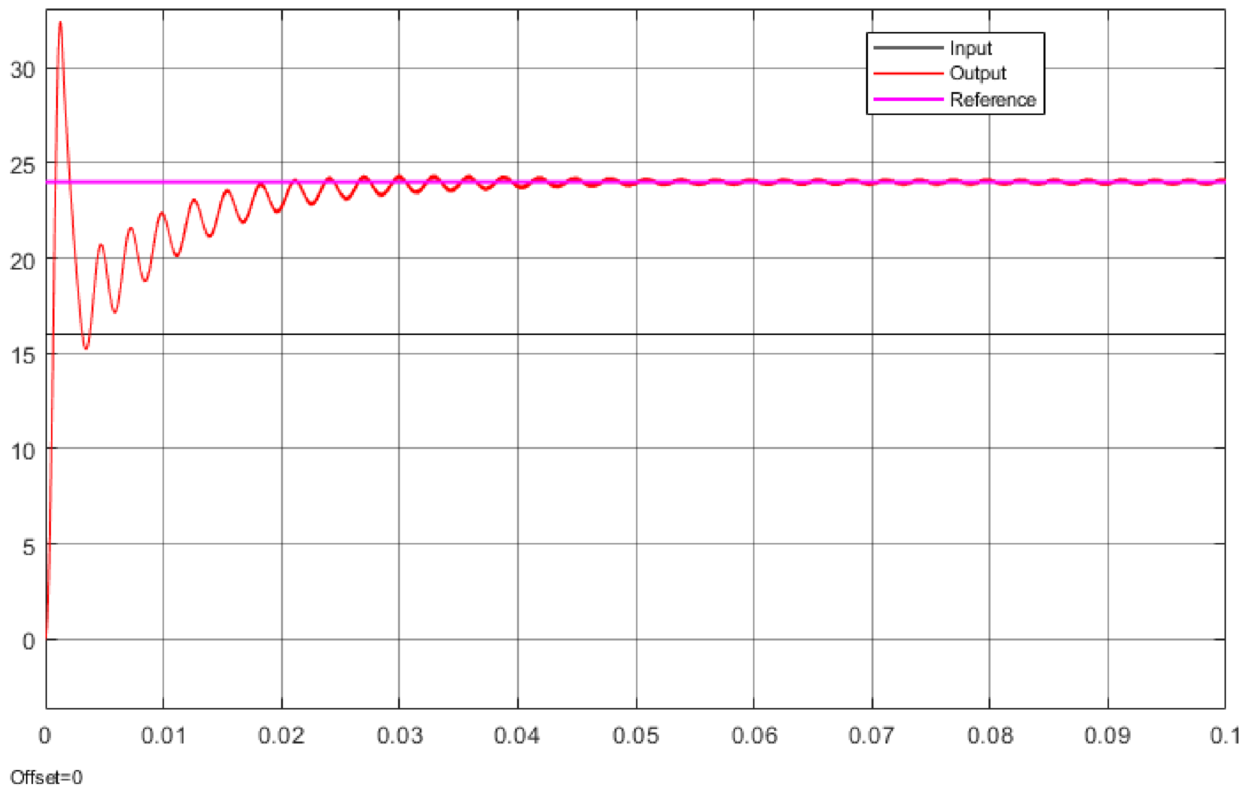
High	2.397e+01
Low	1.366e+01
Amplitude	1.031e+01
+ Edges	2
+ Rise Time	5.848 ms
+ Slew Rate	17.838 (/ms)
- Edges	1
- Fall Time	588.445 μs
- Slew Rate	-14.013 (/ms)

▼ Overshoots / Undershoots

+ Preshoot	67.895 %
+ Overshoot	27.820 %
+ Undershoot	3.750 %
+ Settling Time	--
- Preshoot	52.857 %
- Overshoot	2.443 %
- Undershoot	2.932 %
- Settling Time	--

Figure 14 Part 3 settling time and overshoot with 100 ohms load

2.3.3 With 200 ohms



▼ Transitions

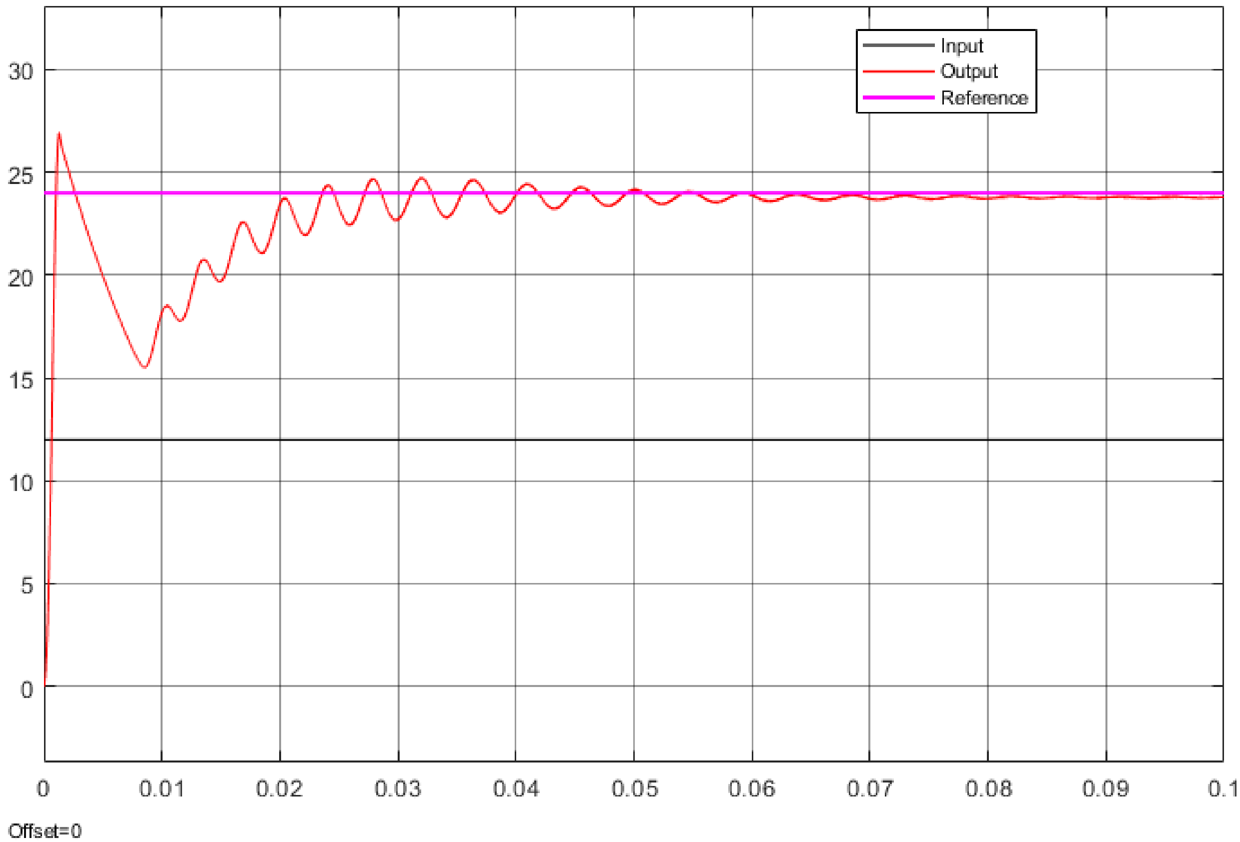
High	2.415e+01
Low	1.539e+01
Amplitude	8.764e+00
+ Edges	2
+ Rise Time	5.698 ms
+ Slew Rate	21.344 (/ms)
- Edges	1
- Fall Time	927.601 μs
- Slew Rate	-7.559 (/ms)

▼ Overshoots / Undershoots

+ Preshoot	83.975 %
+ Overshoot	48.499 %
+ Undershoot	8.993 %
+ Settling Time	--
- Preshoot	94.444 %
- Overshoot	1.999 %
- Undershoot	2.203 %
- Settling Time	--

Figure 15 Part 3 settling time and overshoot with 200 ohms load

2.4 Part 4 with 1000 ohms load



▼ Transitions

High	2.384e+01
Low	1.128e-01
Amplitude	2.373e+01
+ Edges	1
+ Rise Time	655.023 µs
+ Slew Rate	28.978 (/ms)
- Edges	0
- Fall Time	--
- Slew Rate	--

▼ Overshoots / Undershoots

+ Preshoot	0.568 %
+ Overshoot	13.068 %
+ Undershoot	1.998 %
+ Settling Time	19.339 ms

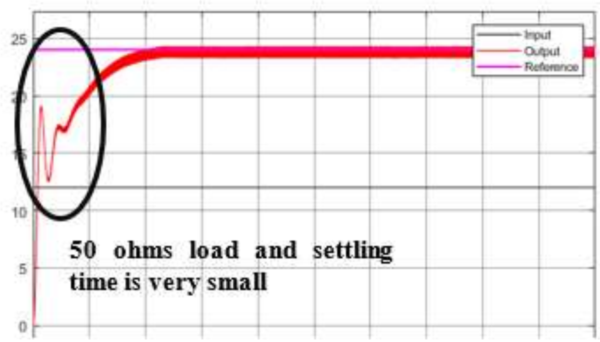
Figure 16 Part 4 settling time and overshoot with 1000 ohms load

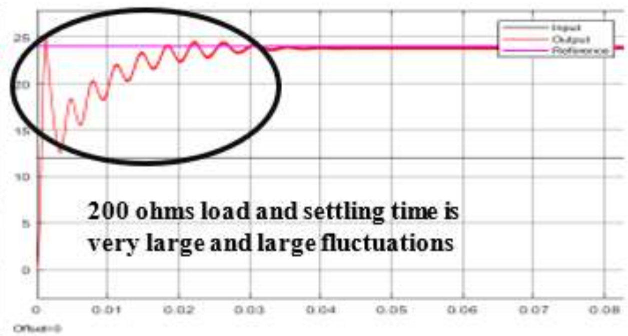
3 Part C

Discuss the system operations based on the above four points.

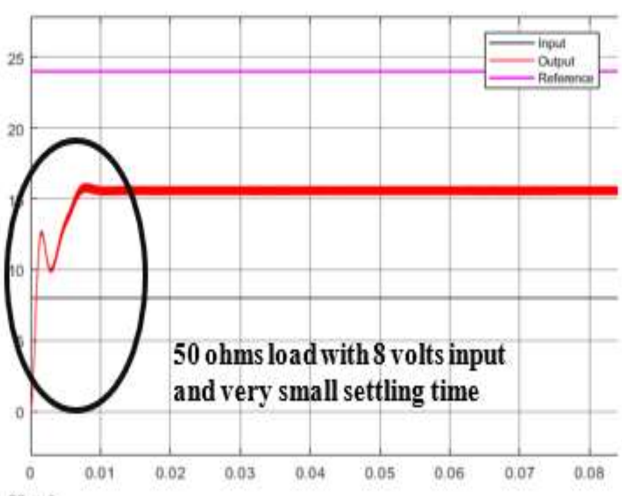
3.1 Discussion

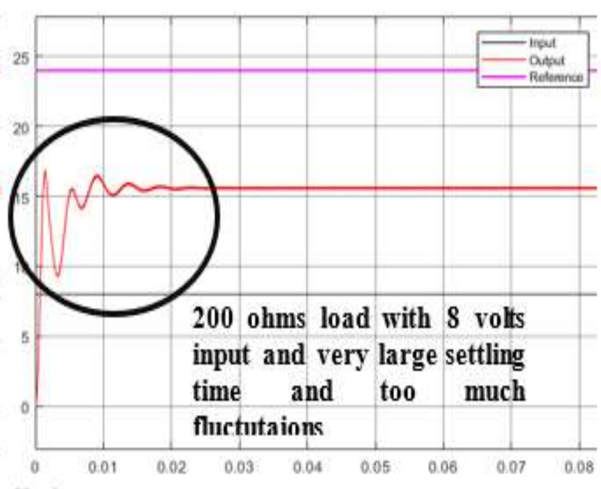
In the first section, point 1, I set the input voltage of the load to 12 volts and the resistance of the load to 50 ohms. It is more stable than 100 and 200 ohms because the load resistance is low and the overshoot is less. Because the load increases by 200 ohms, the overshoot becomes more pronounced as the system fluctuates, but it will eventually reach a steady state, so the system meets the specifications. As a result, the stability time decreases as the load increases and increases as the load decreases.



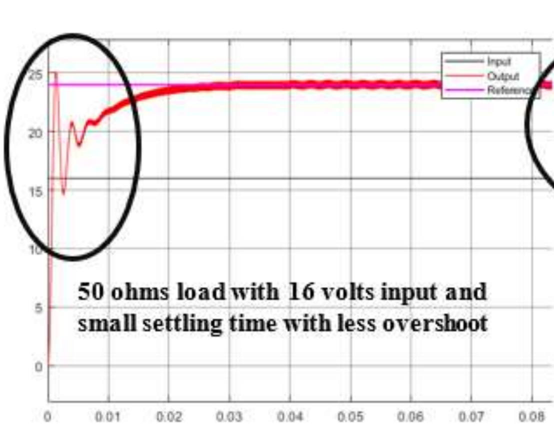


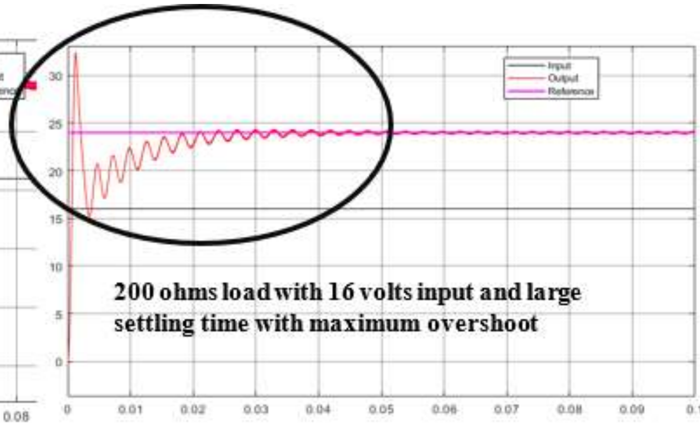
In the second section, the input voltage is set to 8 volts, the load is set to 50, 100, and 200 ohms, the output voltage is decreased, and the stability time is shortened. There are large fluctuations in the 200-ohms resistance compared to the 50-ohms resistance.



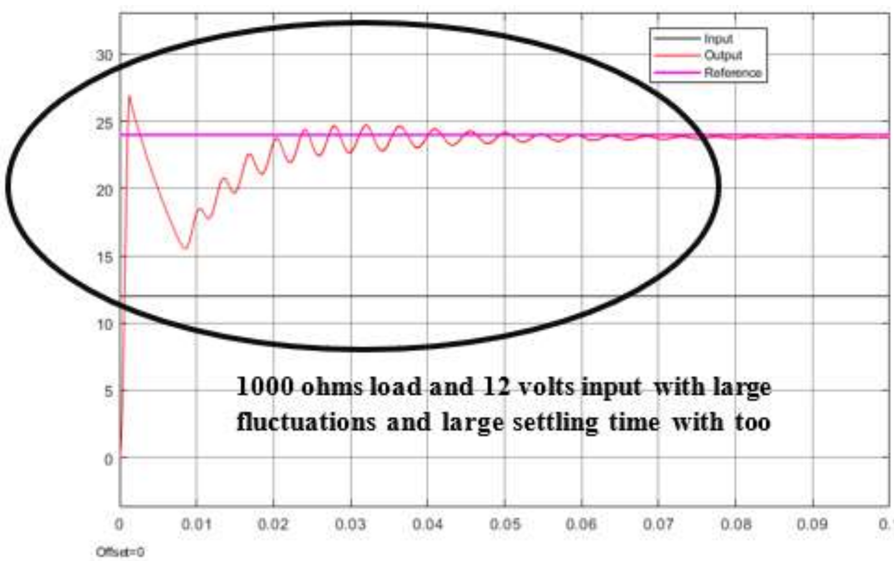


In the third case, the input is close relative to the other instances. Due to the minor difference between the input and output, the overshoot is reduced to 50 ohms because it initially receives more power. As resistance increases, overshoot increases, and settling time decreases in comparison to 50 ohms.





In the final point, the input voltage is 12 volts, and the resistance of the load is 1000 ohms; it draws more current and power, making the system less responsive and requiring more time to stabilize.



As a result, the system stability time decreases, and the overshoot increases as the load increases. However, stability time is increased for small loads, and stabilization time is reduced, resulting in a slight overshoot.