Final Project of Power Supplies

Design and Simulation of DC-DC Forward Converter with Type III Compensator

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Abstract

This report shows the design process and circuit simulation of forward converter. The simulation of compensator is designed and added, so that the converter can form closed-loop feedback. Finally, it shows the time-domain variation of the simulation when the load changes and the reference voltage changes is shown.

Keywords: Forward Converter; Type III Compensator; Design; Simulation

Contents

1 Design of forward converter

My school number is N16590031, which means the penultimate digit T = 3 and the last digit U = 1. According to the requests given in the Brightspace, I need to design a PWM forward converter operating in CCM to meet the following specifications:

$$V_O = 12\ V$$
$$P_{O\min} = 40\ W$$
$$P_{O\max} = 80\ W$$
$$V_I = 20\ V$$
$$V_r / V_O \leq 2\%$$

The value of the dc voltage transfer function is

$$M_{V\,DC} = \frac{V_O}{V_I} = \frac{12}{20} = 0.6$$

The minimum and maximum values of the output current are

$$I_{O\min} = \frac{P_{O\min}}{V_O} = \frac{40}{12} = 3.33\ A$$
$$I_{O\max} = \frac{P_{O\max}}{V_O} = \frac{80}{12} = 6.66\ A$$

The minimum and maximum values of the load resistance are

$$R_{L\min} = \frac{V_O}{I_{O\max}} = \frac{12}{6.66} = 1.8\ \Omega$$
$$R_{L\max} = \frac{V_O}{I_{O\min}} = \frac{12}{3.33} = 3.6\ \Omega$$

Since we can use ideal components in calculations, which means the converter efficiency $\eta = 100\%$. I assume the switching frequency $f_s = 100\ kHz$ and $D \approx 0.4$. The transformer turns ratio is

$$n_1 = \frac{\eta D}{M_{V\,DC}} = \frac{1 \times 0.4}{0.6} = 0.667$$

Pick $n_1 = n_3 = 0.7$. The value of the duty cycle is

$$D = \frac{n_1 M_{V\,DC}}{\eta} = \frac{0.7 \times 0.6}{1} = 0.42$$

Hence, $t_{m(\max)} / T = D = 0.42$. The maximum permissible duty cycle is

$$D_{MAX} = \frac{1}{\frac{n_3}{n_1} + 1} = 0.5$$

Thus, $D < D_{MAX}$.

The approximately minimum inductance is

$$L_{\min} = \frac{R_{L\max}(1-D)}{2f_s} = \frac{3.6\times(1-0.42)}{2\times100\times10^3} = 10.44\ \mu H$$

Let $L = 20\ \mu H$. The approximate peak-to-peak value of the inductor ripple current is

$$\Delta i_L = \frac{V_O(1-D)}{f_s L} = \frac{12\times(1-0.42)}{100\times10^3\times20\times10^{-6}} = 5.8\ A$$

The ripple voltage is

$$V_r = 0.02V_O = 0.02\times12 = 0.24\ V$$

The approximate ESR of the filter capacitor is

$$r_C = \frac{V_r}{\Delta i_L} = \frac{0.24}{5.8} = 41.38\ m\Omega$$

Let $r_C = 40\ m\Omega$. Thus, the filter capacitance is

$$C_{\min} = \frac{1-D}{2f_s r_C} = \frac{1-0.42}{2\times100\times10^3\times40\times10^{-3}} = 72.5\ \mu F$$

Pick $C = 100\ \mu F$. The corner frequency of the low-pass output filter is

$$f_O = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{20\times10^{-6}\times100\times10^{-6}}} = 3.559\ kHz$$

The voltage stresses of the rectifier diodes are

$$V_{D1M} = \frac{V_I}{n_3} = V_{D2M} = \frac{V_I}{n_1} = \frac{20}{0.7} = 28.57\ V$$

and the current stresses of these diodes are

$$I_{D1M\max} = I_{D2M\max} = I_{O\max} + \frac{\Delta i_L}{2} = 6.66 + \frac{5.8}{2} = 9.56\ A$$

The maximum peak current through the primary of the ideal transformer is

$$I_{1\max} = \frac{I_{D1M\max}}{n_1} = \frac{9.56}{0.7} = 13.657\ A$$

Assume that the maximum peak current through the magnetizing inductance is less than 10% of the maximum peak current through the primary of the ideal transformer. Thus,

$$\Delta i_{Lm(\max)} = 0.1 I_{1M\max} = 0.1\times13.657 = 1.366\ A$$

The minimum magnetizing inductance is then

$$L_{m(\min)} = \frac{D\,V_I}{f_s \Delta i_{Lm(\max)}} = \frac{0.42\times20}{100\times10^3\times1.366} = 61.5\ \mu H$$

Pick $L_m = 65\ \mu H$. The stresses of the diode D_3 are

$$V_{D3M} = (\frac{n_3}{n_1}+1)V_I = 2\times20 = 40\ V$$

$$I_{D3M\max} = (\frac{n_1}{n_3})\Delta i_{Lm(\max)} = 1.366\ A$$

The voltage and current stresses of the switch are

$$V_{SM} = (\frac{n_1}{n_3}+1)V_I = 2\times 20 = 40\ V$$

$$I_{SM\max} = I_{1\max} + \Delta i_{Lm(\max)} = 13.657 + 1.366 = 15.023\ A$$

An International Rectifier IRF740 power MOSFET is selected, which has $V_{DSS} = 400\ V$, $I_{SM} = 10\ A$, $r_{DS} = 0.55\ \Omega$, $Q_{g(typ)} = 41\ nC$, $Q_{g\max} = 60\ nC$, and $C_O = 100\ pF$. Two MBR2540 Schottky barrier diodes are chosen, which has $I_{DM} = 25\ A$, $V_{DM} = 40\ V$, $V_F = 0.3\ V$ and $R_F = 16\ m\Omega$. A fast recovery MR826 diode is selected with $V_{DM} = 600\ V$ and $I_{DM(AV)} = 5\ A$.

We will calculate power losses for $P_{O\max} = 80\ W$ and $V_I = 20\ V$. The conduction power loss in the MOSFET is

$$P_{rDS} = \frac{r_{DS} D I_{O\max}^2}{n_1^2} = \frac{0.55\times 0.42\times 6.66^2}{0.7^2} = 20.91\ W$$

the switching loss is

$$P_{SW} = f_s C_O V_I^2 = 10^5 \times 100\times 10^{-12} \times 20^2 = 0.004\ W$$

Assuming $r_{T1} = 50\ m\Omega$,

$$P_{rT1} = \frac{r_{T1} D I_{O\max}^2}{n_1^2} = \frac{0.05\times 0.42\times 6.66^2}{0.7^2} = 1.901\ W$$

The power loss due to R_F in diode D_1 is

$$P_{RF1} = D R_F I_{O\max}^2 = 0.42\times 0.016\times 6.66^2 = 0.298\ W$$

the power loss due to V_F in diode D_1 is

$$P_{VF1} = V_F I_{O\max} D = 0.3\times 6.66\times 0.42 = 0.839\ W$$

resulting in the conduction loss in diode D_1

$$P_{D1} = P_{RF1} + P_{VF1} = 0.298 + 0.839 = 1.137\ W$$

Assuming $r_{T2} = 10\ m\Omega$,

$$P_{rT2} = D r_{T2} I_{O\max}^2 = 0.42\times 0.01\times 6.66^2 = 0.186\ W$$

Hence, the power loss in both primary and secondary windings is

$$P_{rT} = P_{rT1} + P_{rT2} = 1.901 + 0.186 = 2.087\ W$$

The power loss due to R_F in diode D_2 is

$$P_{RF2} = (1-D) R_F I_{O\max}^2 = (1-0.42)\times 0.016\times 6.66^2 = 0.412\ W$$

the power loss due to V_F in diode D_2 is

$$P_{VF2} = (1-D) V_F I_{O\max} = (1-0.42)\times 0.3\times 6.66 = 1.159\ W$$

The conduction loss in diode D_2 is

$$P_{D2} = P_{RF2} + P_{VF2} = 0.412 + 1.159 = 2.73\ W$$

Assuming that the dc ESR of the inductor is $r_L = 15\ m\Omega$, one obtains the power loss in the inductor ESR

$$\mathrm{P}_{\mathrm{r}L} = r_L I_{O\max}^2 = 0.015 \times 6.66^2 = 0.665\ W$$

the power loss in the capacitor ESR

$$\mathrm{P}_{\mathrm{r}C} = \frac{r_C(\Delta i_L)^2}{12} = \frac{0.04 \times 5.8^2}{12} = 0.112\ W$$

the total power loss

$$\begin{aligned} P_{LS} &= \mathrm{P}_{\mathrm{r}DS} + P_{SW} + \mathrm{P}_{\mathrm{r}T1} + \mathrm{P}_{\mathrm{r}T2} + P_{D1} + P_{D2} + \mathrm{P}_{\mathrm{r}L} + \mathrm{P}_{\mathrm{r}C} \\ &= 20.91 + 0.004 + 1.901 + 0.186 + 1.137 + 2.73 + 0.665 + 0.112 = 27.645\ W \end{aligned}$$

and the efficiency of the converter

$$\eta = \frac{P_{O\max}}{P_{O\max} + P_{LS}} = \frac{80}{80 + 27.645} = 74.32\%$$

2 Results without compensator

After the calculated values of components are inputted into the open-loop forward converter, the analog circuit is shown in Figure 2.1. (I did not input the values by creating a .m file since it is not a complex system and I can change the value more conveniently.)

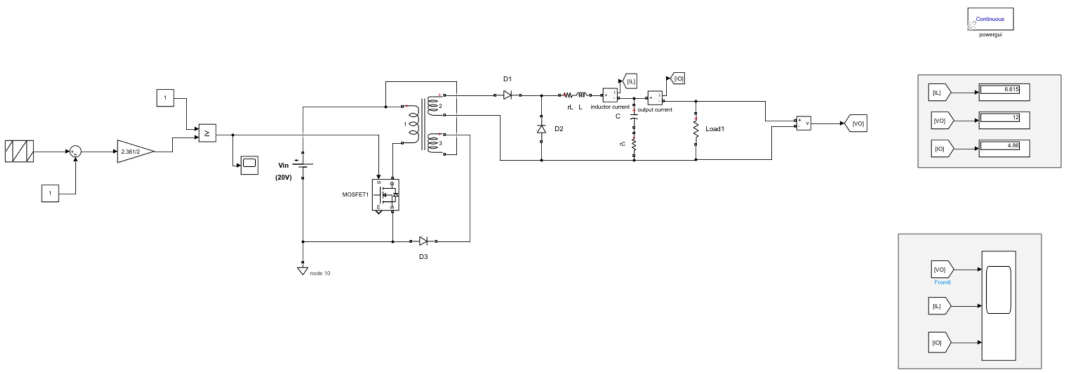

Fig 2.1 Simulation of open-loop forward converter

Through observation, it can also be found that the PWM wave (shown in Figure 2.2) is generated normally, and the duty cycle is 0.42, which is same as the calculated value.

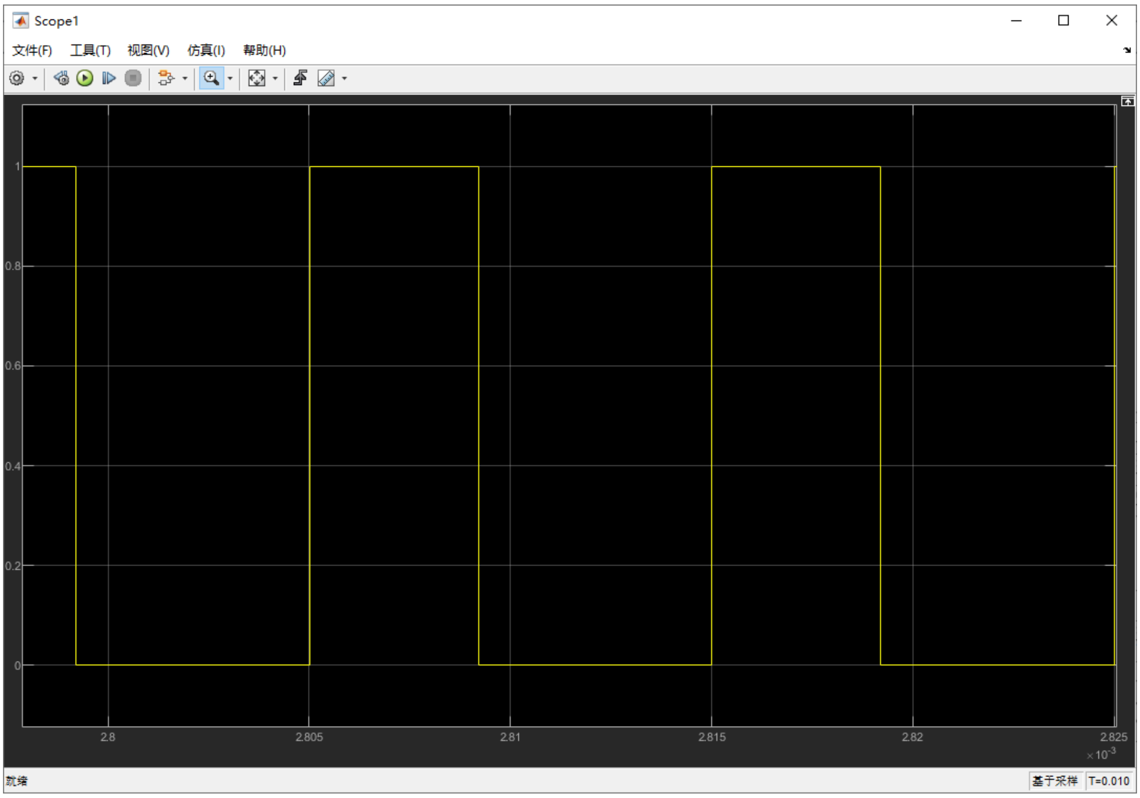

Fig 2.2 PWM waveform

And the waveforms of inductor current i_L, output voltage V_O and output current I_O are shown in Figure 2.3. We can see that after only 0.001 second oscillation, the output voltage is stable at 12V.

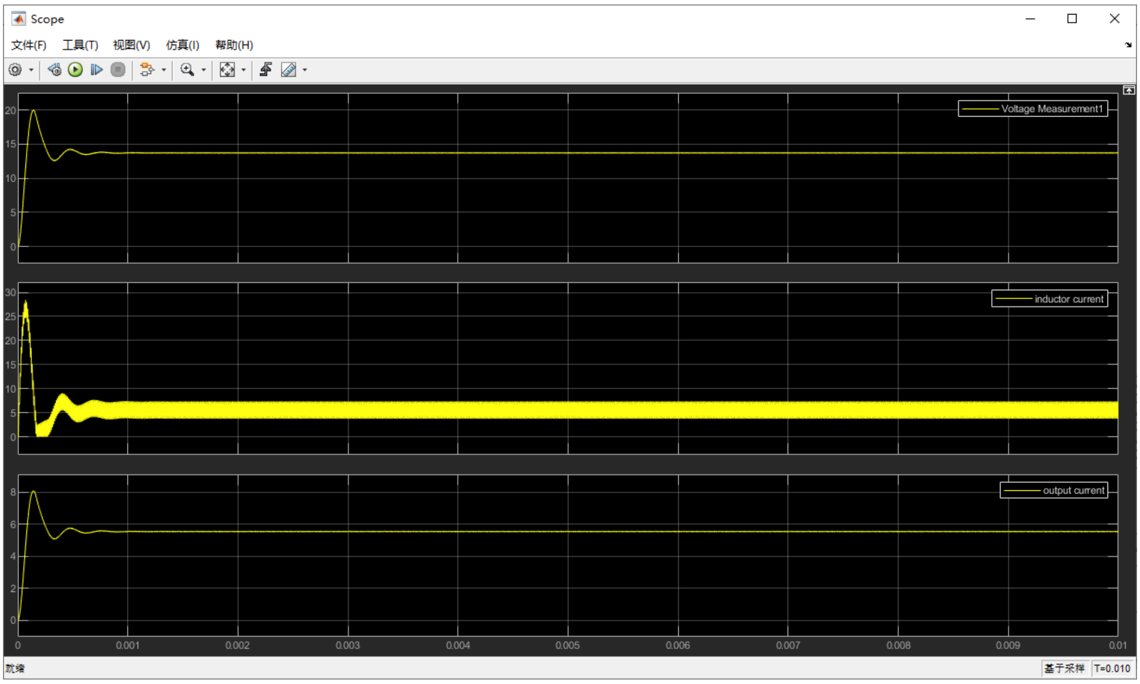

Fig 2.3 Waveforms of inductor and ouput

The simulated values of output voltage, inductor current and output current are shown in the Figure 2.4. We can see that these values is in the scope of the calculated values.

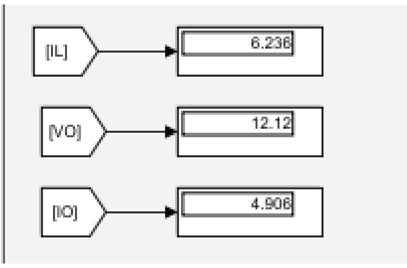

Fig 2.4 Simulated values of inductor and ouput

3 Design of type III compensator

To begin with, I establish the Simulink model of type III compensator according to the type III error amplifier from Mohan's example, which is shown in Figure 3.1.

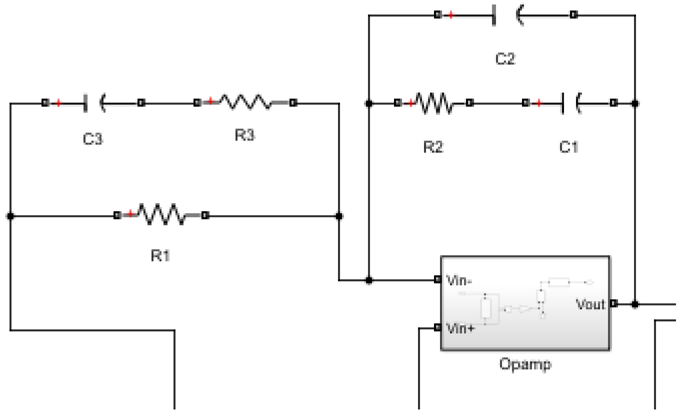

Fig 3.1 Type III error amplifier

To design the compensator, I need to know the transfer function of the forward converter (which is similar with the buck converter). According to the transfer function and the calculated values above, we can draw the Bode plots with Matlab and find the control plant's gain G_P and phase Φ_P at desired crossover frequency ω_C.

According to the information consulted from the internet, I find the transfer function of the buck converter is

$$G_{vd}(s) = \frac{V_O(s)}{D(s)} = \frac{(1+sCr_C)V_I}{1+s^2LC(1+\frac{r_C}{R})+s(\frac{L}{R}+Cr_C)}$$

After disassembling the polynomial and moving the terms in the equation according to the power of s, it can be written as

$$G_{vd}(s) = \frac{V_ICr_Cs+V_I}{LC(1+\frac{r_C}{R})s^2+(\frac{L}{R}+Cr_C)s+1}$$

Calculate the coefficients before s and s^2 respectively:

$$V_ICr_C = 20\times100\times10^{-6}\times40\times10^{-3} = 8\times10^{-5}$$

$$LC(1+\frac{r_C}{R}) = 20\times10^{-6}\times100\times10^{-6}\times(1+\frac{40\times10^{-3}}{2.47}) = 2.0323887\times10^{-9}$$

$$\frac{L}{R}+Cr_C = \frac{20\times10^{-6}}{2.47}+100\times10^{-6}\times40\times10^{-3} = 1.209717\times10^{-7}$$

Then I use the Matlab to draw the Bode plots. The Matlab code is in the file: Bode plots.m. The Bode plot of forward converter is shown in Figure 3.2.

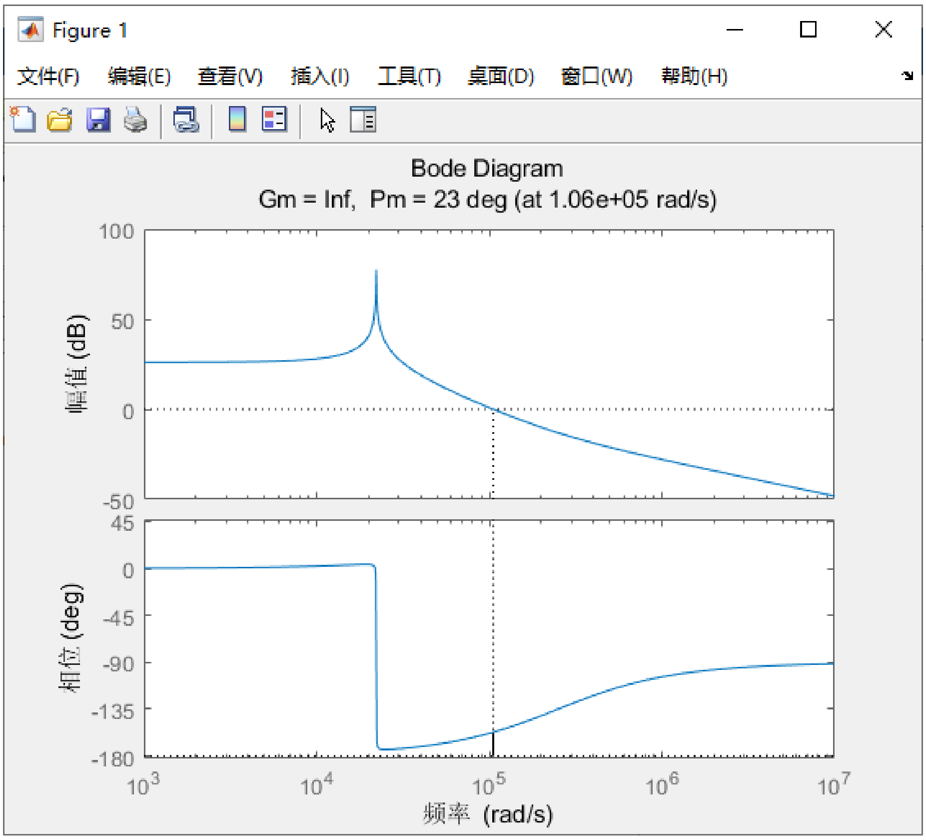

Fig 3.2 Bode plot of forward converter

The phase margin is required to be larger than 45°. Here, the same bandwidth is targeted, and the phase margin is targeted at 60°. From Fig. 1.5, one can find that at 30000 rad/s, the plant's gain G_P is 27.8 dB or 24.5471, and the phase Φ_p is -173°. I will calculate the compensator below. I place the compensator's maximum phase boost frequency at the target crossover frequency, that is $\omega_m = \omega_C = 30000\ rad/s$. By choosing $R_1 = 30\ k\Omega$ and following the procedure, we get the following component values:

The tangent value b:

$$b = \tan(\frac{\Phi_m - \Phi_p}{2} - \frac{\pi}{4}) = \tan 71.5^\circ = 2.9887$$

The zero and pole separation factor k:

$$\sqrt{k} = b + \sqrt{b^2 + 1} = 6.14026$$

The zero's and pole's frequency:

$$\omega_z = \frac{\omega_C}{\sqrt{k}} = 4885.7866$$

$$\omega_p = \sqrt{k}\omega_C = 184207.8$$

The compensator's gain K:

$$K = \frac{\omega_C}{G_P k} = \frac{30000}{24.5471 \times 37.7028} = 32.4151$$

Calculate C_3:

$$C_3 = \frac{1}{R_1}(\frac{1}{\omega_z} - \frac{1}{\omega_p}) = \frac{1}{30000} \times (\frac{1}{4885.7866} - \frac{1}{184207.8}) = 6.64\ nF$$

Calculate C_1:

$$C_1 = \frac{\omega_z}{\omega_p R_1 K} = \frac{4885.7866}{184207.8 \times 30000 \times 32.4151} = 27.27\ nF$$

Calculate C_2:

$$C_2 = \frac{1}{R_1 K} - C_1 = \frac{1}{30000 \times 32.4151} - 27.27 \times 10^{-9} = 1\ \mu F$$

Calculate R_2:

$$R_2 = \frac{C_1 + C_2}{C_1 C_2 \omega_p} = \frac{27.27 \times 10^{-9} + 1 \times 10^{-6}}{27.27 \times 10^{-9} \times 1 \times 10^{-6} \times 184207.8} = 204.4\ \Omega$$

Calculate R_3:

$$R_3 = \frac{1}{C_3 \omega_z} - R_1 = \frac{1}{6.64 \times 10^{-9} \times 4885.7866} - 30000 = 824.6\ \Omega$$

After calculating all the values of components in the compensator, I will use these to get the Bode plot of the compensator. We already have the transfer function of the Type III compensator:

$$C(s) = \frac{V_o}{V_i} = -\frac{(sC_2R_2 + 1)[sC_3(R_1 + R_3) + 1]}{R_1(C_1 + C_2)s(s\frac{C_1C_2}{C_1 + C_2}R_2 + 1)(sC_3R_3 + 1)}$$

Spread the polynomials of numerator and denominator:

$$C(s) = \frac{V_o}{V_i} = -\frac{s^2 C_2 C_3 R_2 (R_1 + R_3) + s(C_2R_2 + C_3R_1 + C_3R_3) + 1}{s^3 R_1R_2R_3C_1C_2C_3 + s^2[R_1R_2C_1C_2 + R_1R_3C_3(C_1 + C_2)] + sR_1(C_1 + C_2)}$$

Calculate the coefficients before s, s^2 and s^3 respectively:

$$C_2C_3R_2(R_1 + R_3) = 1\times10^{-6} \times 6.64\times10^{-9} \times 204.4 \times (3\times10^4 + 824.6) = 4.183564\times10^{-8}$$

$$C_2R_2 + C_3R_1 + C_3R_3 = 1\times10^{-6} \times 204.4 + 6.64\times10^{-9} \times 3\times10^4 + 6.64\times10^{-9} \times 824.6 = 4.09075\times10^{-4}$$

$$R_1R_2R_3C_1C_2C_3 = 3\times10^4 \times 204.4 \times 824.6 \times 27.27\times10^{-9} \times 1\times10^{-6} \times 6.64\times10^{-9} = 9.15585\times10^{-13}$$

$$\begin{aligned} R_1R_2C_1C_2 + R_1R_3C_3(C_1 + C_2) &= 3\times10^4 \times 204.4 \times 27.27\times10^{-9} \times 1\times10^{-6} \\ &+ 3\times10^4 \times 824.6 \times 6.64\times10^{-9} \times (27.27\times10^{-9} + 1\times10^{-6}) = 3.3591499\times10^{-7} \end{aligned}$$

$$R_1(C_1 + C_2) = 3\times10^4 \times (27.27\times10^{-9} + 1\times10^{-6}) = 3.081\times10^{-2}$$

Then I use the Matlab to draw the Bode plots. The Matlab code is in the file: Bode plots.m. The Bode plot of forward converter is shown in Figure 3.3.

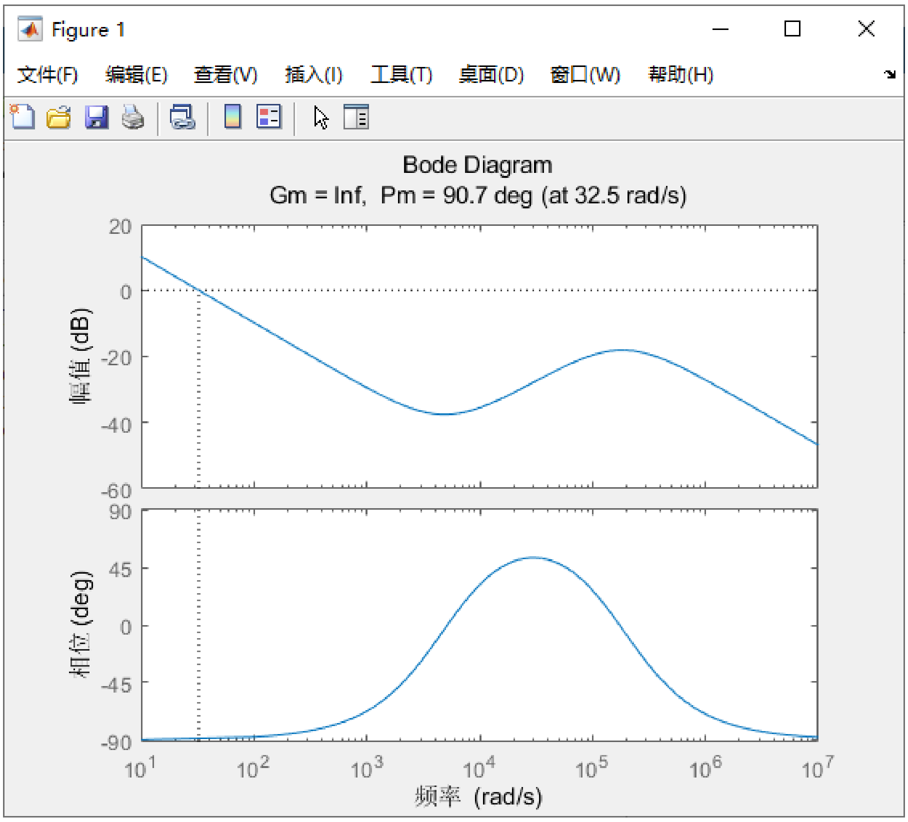

Fig 3.3 Bode plot of compensator

By adding the Bode diagram of the converter and the Bode diagram of the compensator, it can be found that the slope of the curve is – 20 dB at the crossing frequency. The phase margin is greater than 45 degrees and less than 60 degrees. Therefore, the system is stable.

4 Results with compensator

4.1 Schematics and waveforms without step change

After the calculated values of components are inputted into the closed-loop forward converter and compensator, the analog circuit is shown in Figure 4.1.1.

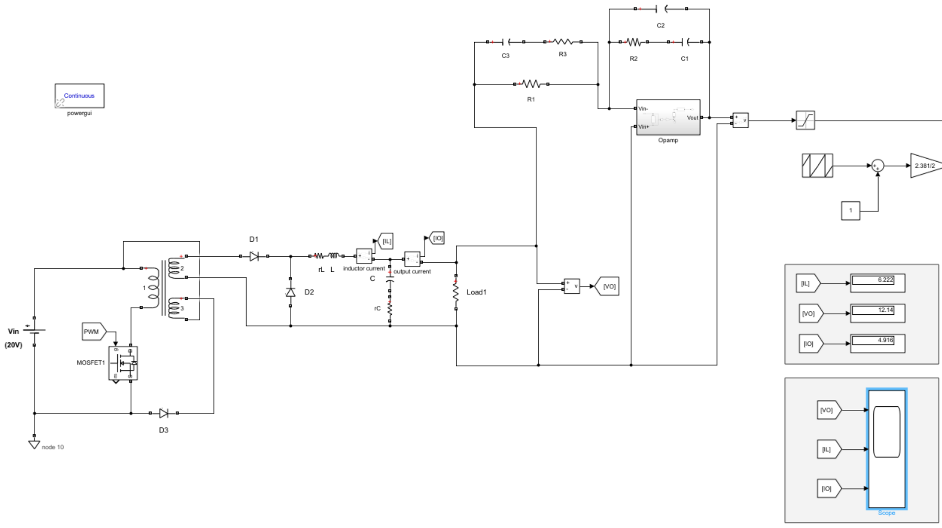

Fig 4.1.1 Simulation of closed-loop forward converter without step change

And the waveforms of inductor current i_L, output voltage V_O and output current I_O are shown in Figure 4.1.2.

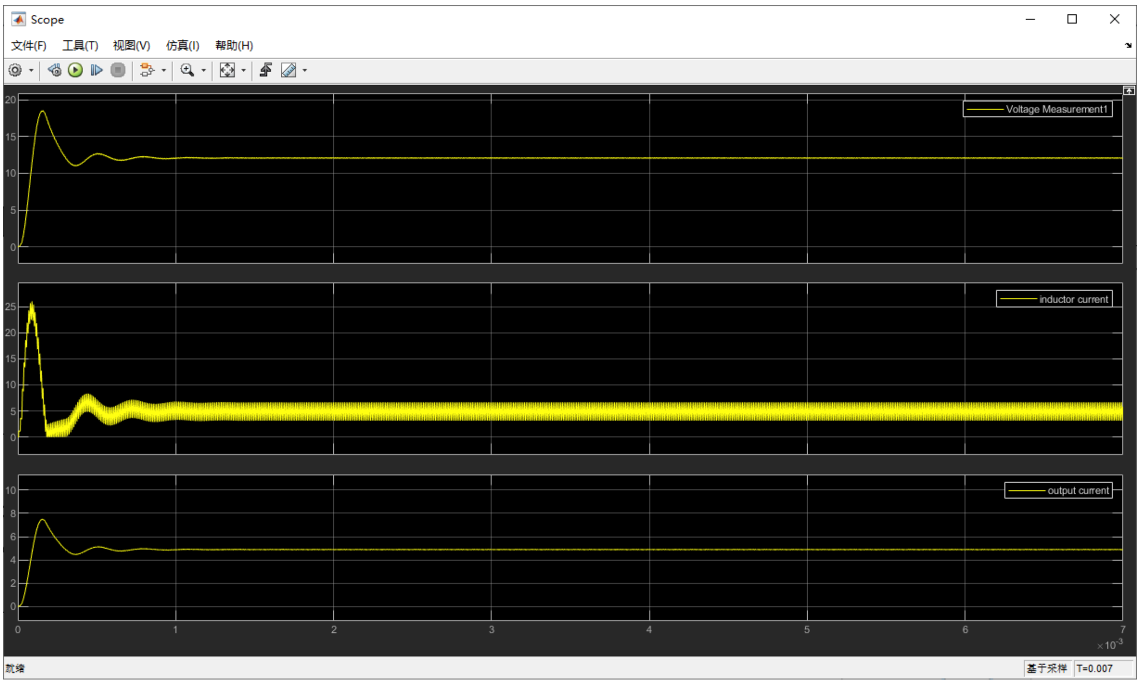

Fig 4.1.2 Waveforms of inductor and ouput without step change

The simulated values of output voltage, inductor current and output current are shown in the Figure 4.1.3. We can see that these values is in the range of the calculated values.

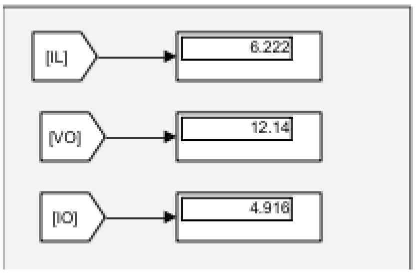

Fig 4.1.3 Simulated values of inductor and ouput without step change

4.2 Schematics and waveforms with step change

I add a load change (full load to 50% and back) and step reference voltage change (at least 20% step up from nominal value).

Load change is finished by adding a signal builder module, which is shown in Figure 4.2.1. Connect the signal generator with the switch, the switch is connected in parallel with load2, and load2 is connected in series with load1. When the signal is 1, the switch is closed, load2 is short circuited, and only load1 is in the circuit. When the signal is 0, the switch is disconnected and load2 and load1 are connected in series in the circuit. The time for the signal to change from 1 to 0 is at 1.5 ms, and the time for the signal to change from 0 to 1 is at 3 ms.

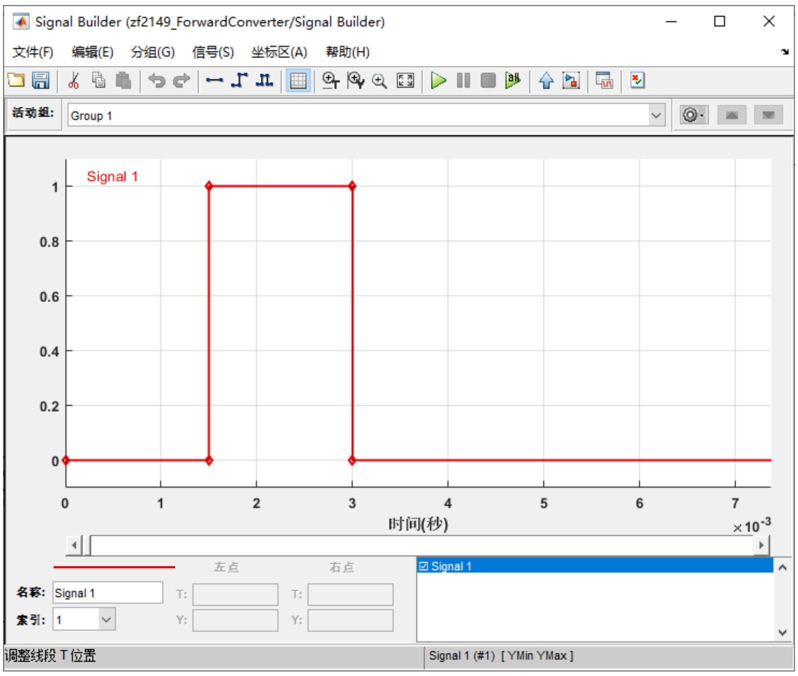

Fig 4.2.1 Setting of signal builder

Reference voltage change is finished by adding a controlled voltage source module. Connect it to the Vin+ end of the Opamp module and control it to rise by 20% with the step signal occurring at 5 ms.

After setting down all the components, the analog circuit is shown in Figure 4.2.2.

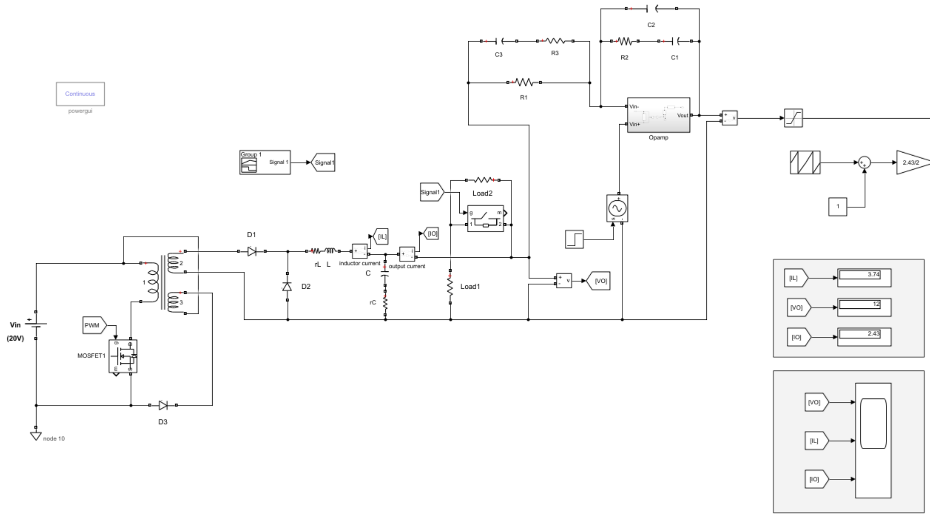

Fig 4.2.2 Simulation of closed-loop forward converter with step change

And the waveforms of inductor current i_L, output voltage V_O and output current I_O with step load change and step reference voltage change are shown in Figure 4.2.3.

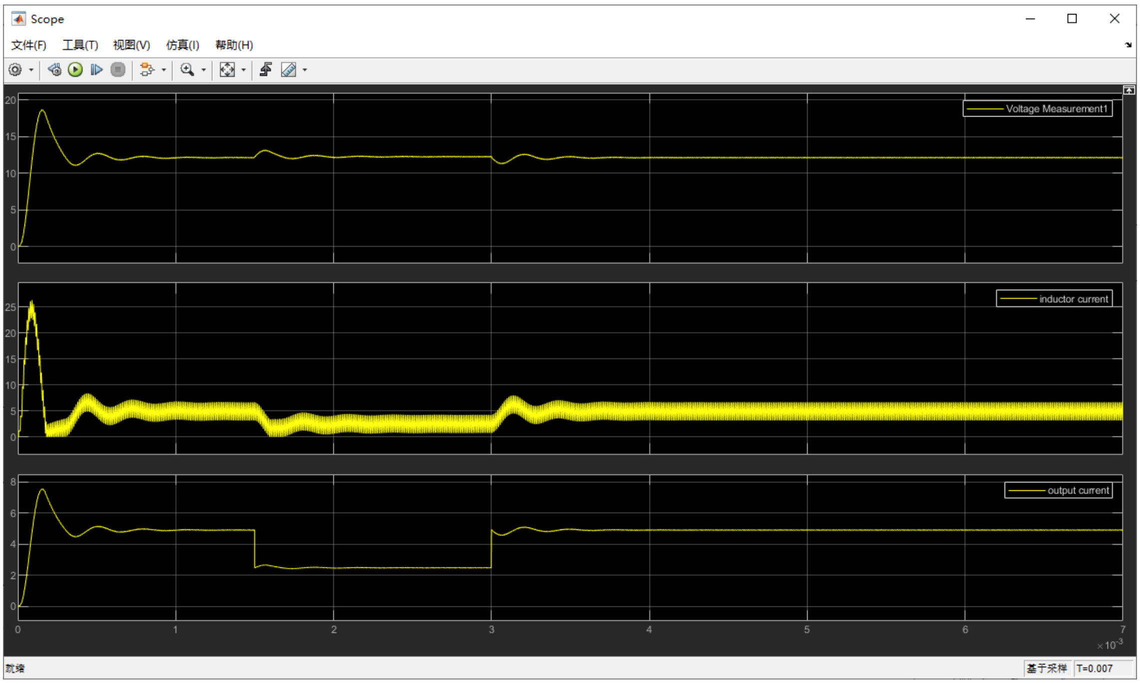

Fig 4.2.3 Waveforms of inductor and ouput with step change

We can observe that after the output voltage is stable, the output voltage will produce slight oscillation at the time point when the load is changed from 50% to full load and from full load to 50%. However, due to the function of compensator, the output voltage will quickly return to the original value. When the reference voltage is increased by 20%, the output voltage does not change. Therefore, my project is successful.

5 Conclusion

The design of this subject makes full use of the knowledge learned in the course of power supply, and also exercises our ability to design a circuit system. In this design, I used the professional knowledge learned in the class and combined with the guidance of the professor to complete the Simulink simulation design and realized the relevant functions according to the requirements. However, there are still some problems that need to be improved: the crossing frequency of the compensator is small and the change of the reference voltage does not cause any change of the output voltage. But the experience of completing this project has benefited me a lot. I am very thankful for the instruction and help of the professor and teaching assistant!