Seminar 8

Wang XingYi 2226215258

1. Topic

In this topic, we are required to design a single-phase full-bridge Boost-PFC circuit. The input voltage is 220V, 50Hz, and the output voltage is 380V, with a power of 3kW.

To be more specific, we need to:

1) Analyze the operating principles of the single-phase full-bridge Boost-PFC circuit.

2) Implement current loop control using hysteresis comparator control with voltage open-loop.

3) Build on (2) by adding an outer voltage loop for control.

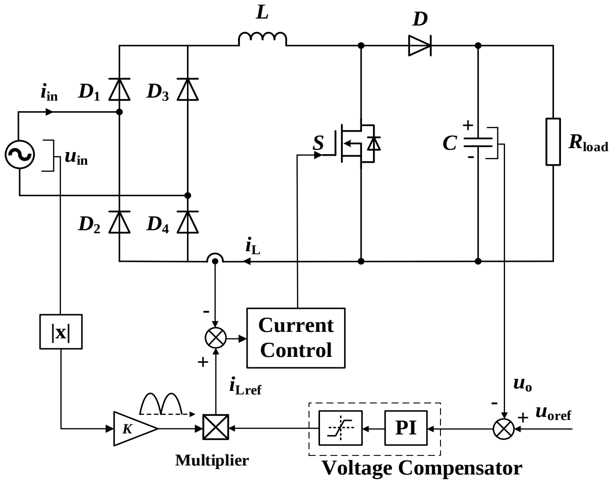

Figure 1: Circuit Topology

2. Simulation Model

In this topic, we build on two simulation models corresponding to situations with voltage open-loop and closed-loop.

2.1 Hysteresis Control with Voltage Open-Loop

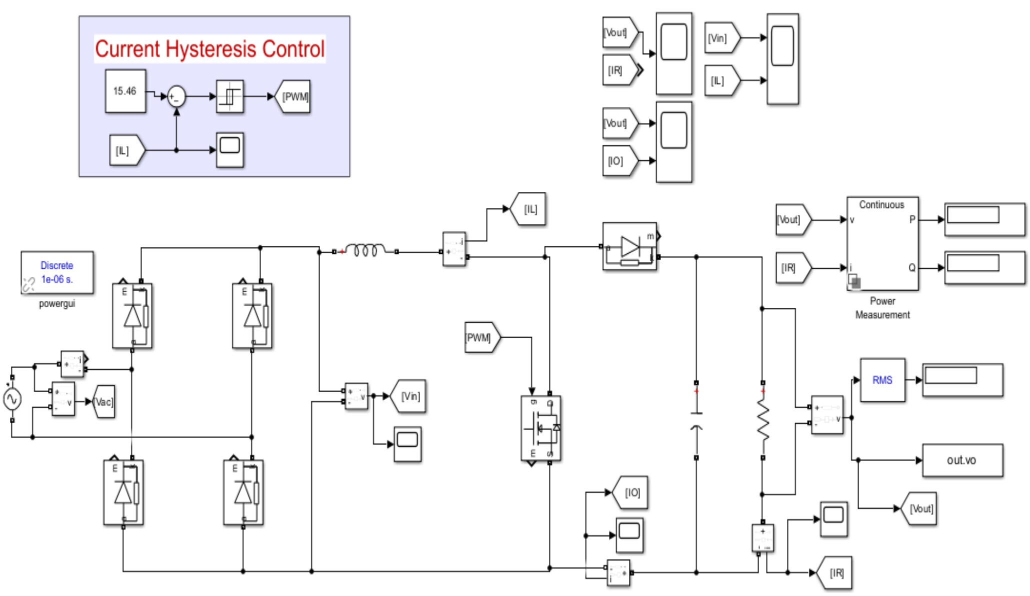

Figure 2: Simulation Model of Hysteresis Control

As required in the question, we set the voltage open-loop, and set the current loop with hysteresis control. By limiting the value of the inductor current within a given range with the hysteresis control, we can change the duty cycle of the boost circuit simultaneously. Therefore, the output DC voltage could be maintained at the desired level. After several tests, we set commanding wave as a constant value, which is the average value of the inductor current, 15.46A.

2.2 Power Factor Correction with Outer Voltage Loop

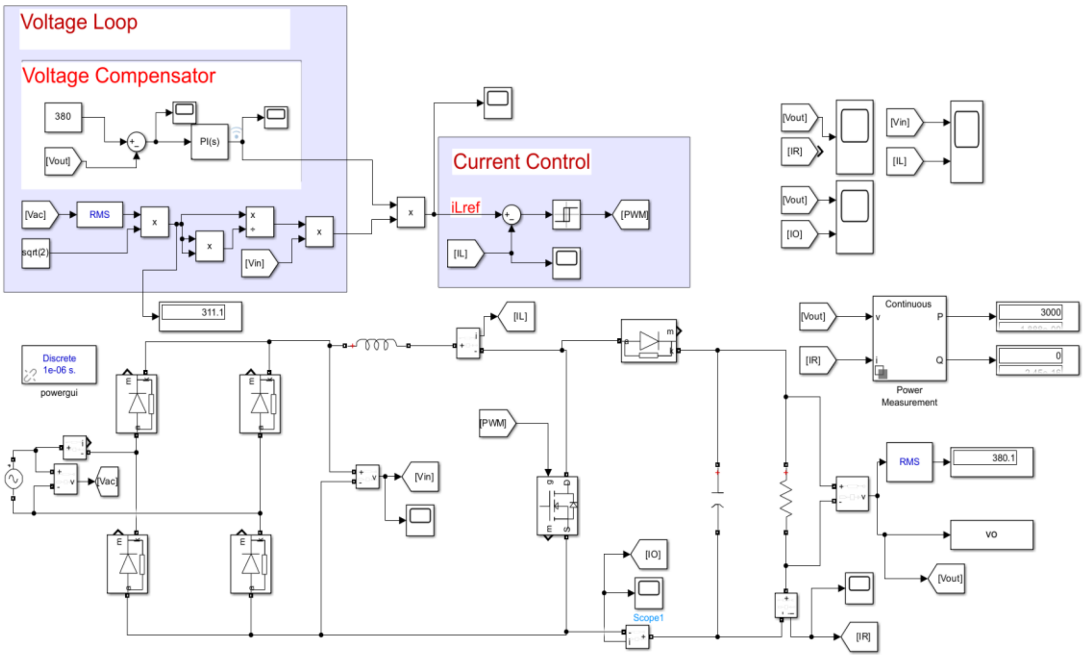

Figure 3: Simulation Model of PFC

On the basis of the hysteresis control, we add an extra outer voltage loop to achieve Power Factor Correction, which can output the reference inductor current, replacing the commanding wave of the previous model. Simultaneously, this outer voltage loop can make the power factor on the grid side close to 1.

3. Parameter Setup

3.1 Major Parameter

Control Method	Vac(rms)	L	C	Vo	fline	R	Pout
Hysteresis	220V	700 μH	470 $\mu F \times 3$	380V	50Hz	48.13ohm	3kW

The specific value of the load resistor can be calculated with the given parameters:

$$R = \frac{U_O^2}{P_{OUT}} = 48.13\,(\Omega)$$

3.2 Device Parameter

Figure 4: Parameter of Relay Block

In this part, we set the width of the inductor current as 0.1A.

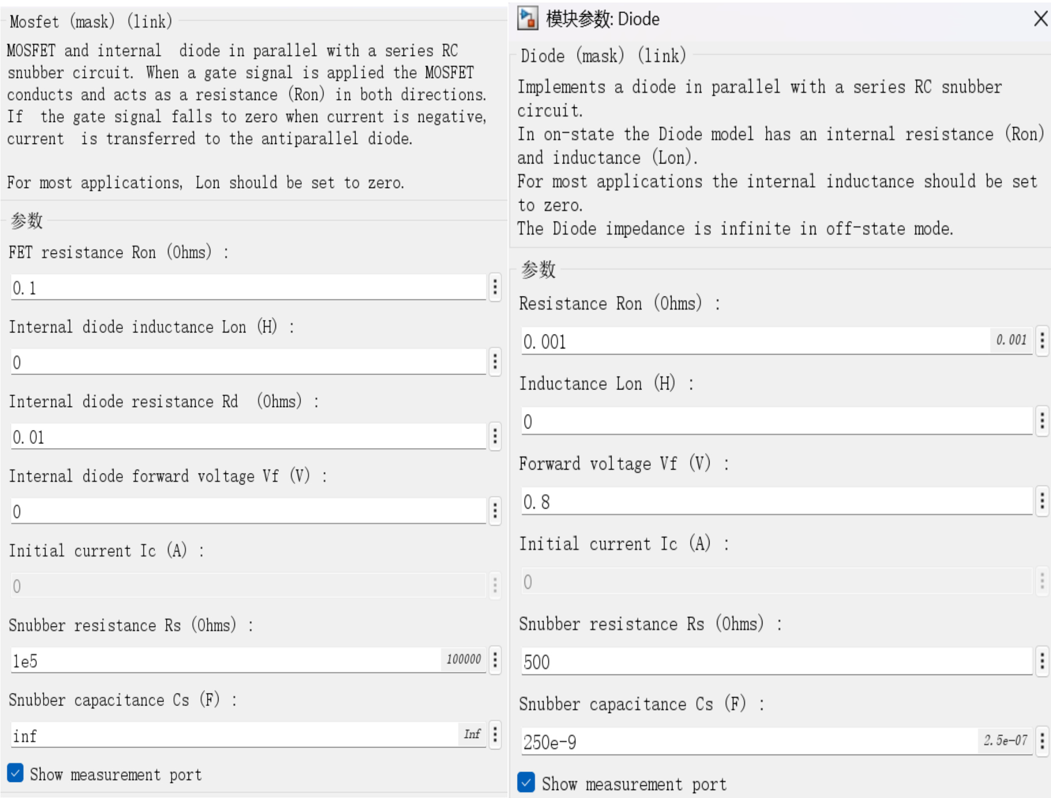

Figure 5: Parameter of Mosfet (L) and Diode (R)

Figure 6: Parameter of PI Block

4. Simulation Results

4.1 Operating Principle

Let's review the basic principle of the BOOST circuit. When the switch device Q is on, the power side charges the inductor, and the inductor current rises. When the switch tube Q is off, the voltage of the output side is higher than that of the input side, the inductance voltage is reversed, and the inductor current is reduced. Therefore, the output voltage and inductor current can be adjusted by controlling the duty cycle of the switch.

The controller must meet the following two requirements:

1) To achieve the output DC voltage regulation, so that it reaches the given value;

2) Ensure that the current on the grid side is sinusoidal, and the power factor is 1.

For this purpose, single-phase PFC double closed loop control with voltage outer loop and current inner loop is adopted.

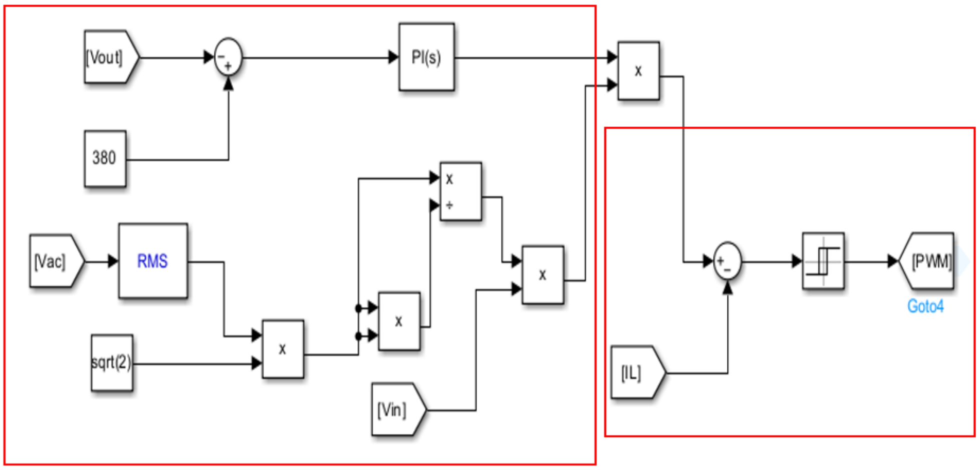

Figure 7 :Closed loop control structure

The left voltage outer loop controls the output of the target inductance current, and the right uses the hysteresis loop pulse width control to make the actual inductance current track the target inductance current. The hysteresis width is 0.1A.

The final effect achieved by this group is shown in the figure below. The first picture shows the voltage and current waveform of the input side, and the two realize the same phase; The second figure is the output voltage waveform, which fluctuates around 380V, the measured RMS value is 380.1V, and the output power is 3001watts.

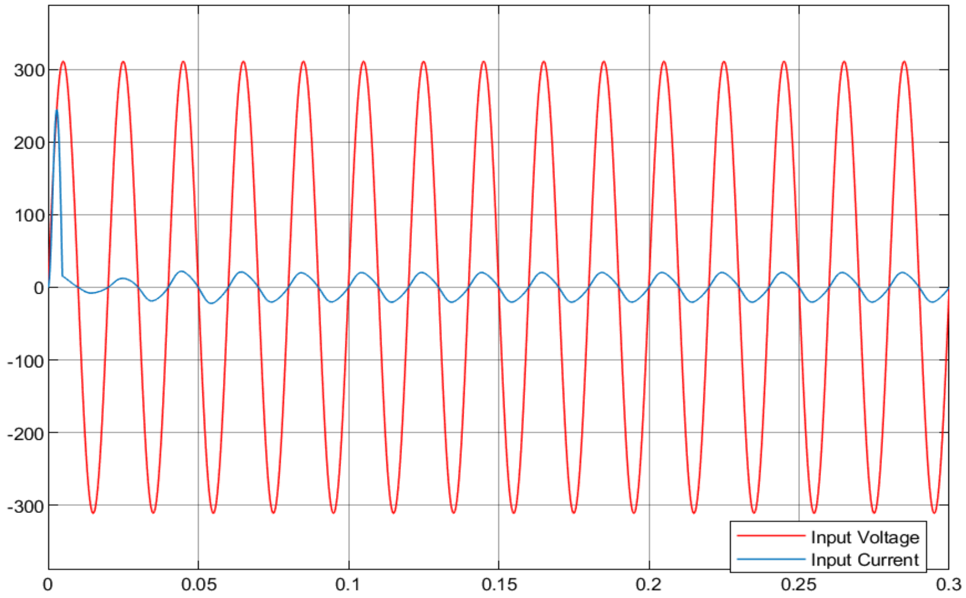

Figure 8: Input voltage and current waveform

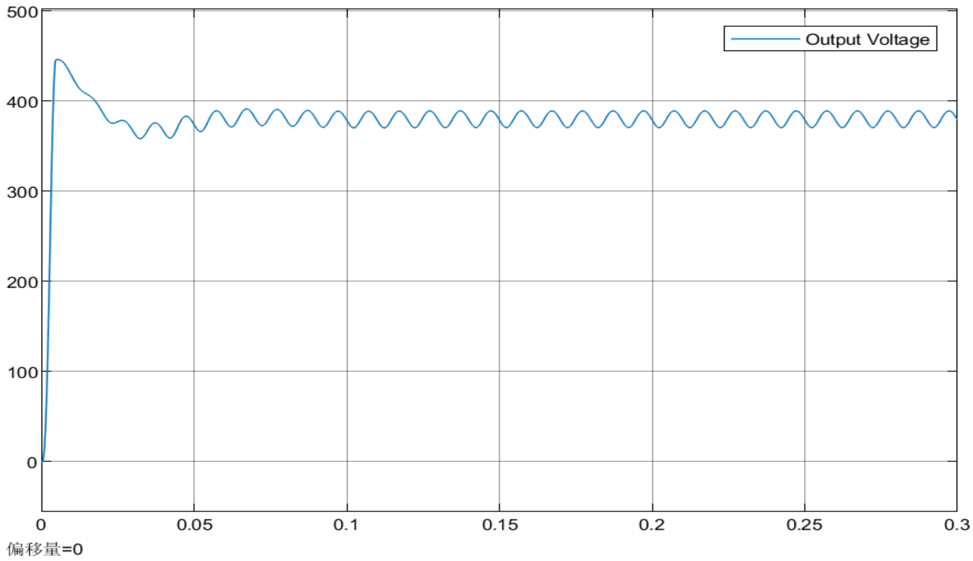

Figure 9: Output voltage waveform

4.2 Hysteresis Control with Voltage Open-Loop

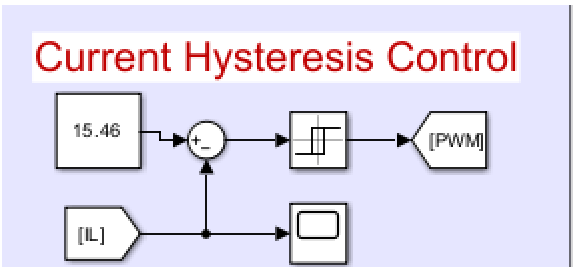

Figure10 : Control Circuit

In the second task, we use the average value of the inductor's current as the commanding wave, and compare with the real output current. Then, we check the output voltage and power. According to the topic, the ideal output voltage's RMS value is 380V and the ideal output power is 3000W. What's more, we hope the reactive power Q is close to 0.

After continuously adjusting the reference current value based on the output voltage and power, the final reference current obtained was 15.46A. Then, we can get the RMS value of the output voltage and power.

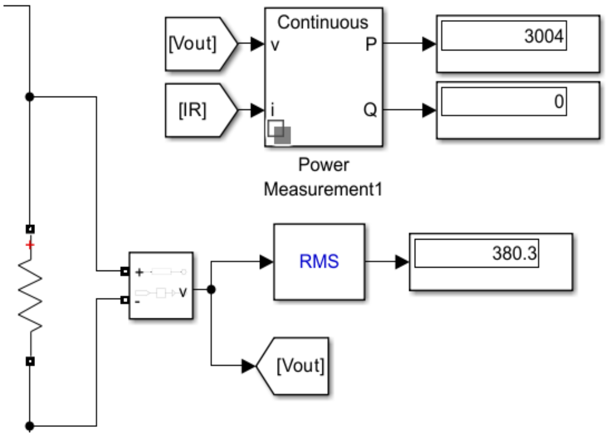

Figure11: Output Voltage and Power

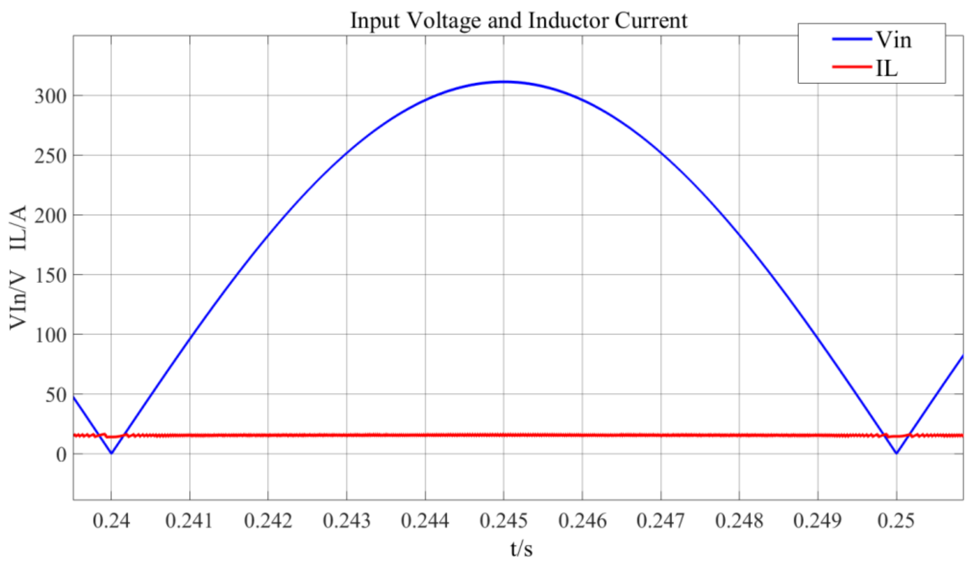

Figure12: Output Voltage and Power

From this picture, we can find that the inductor current is controlled in a small boundary near the theoretical value 15.46A.

4.3 Power Factor Correction with Outer Voltage Loop

4.3.1 Control Circuit

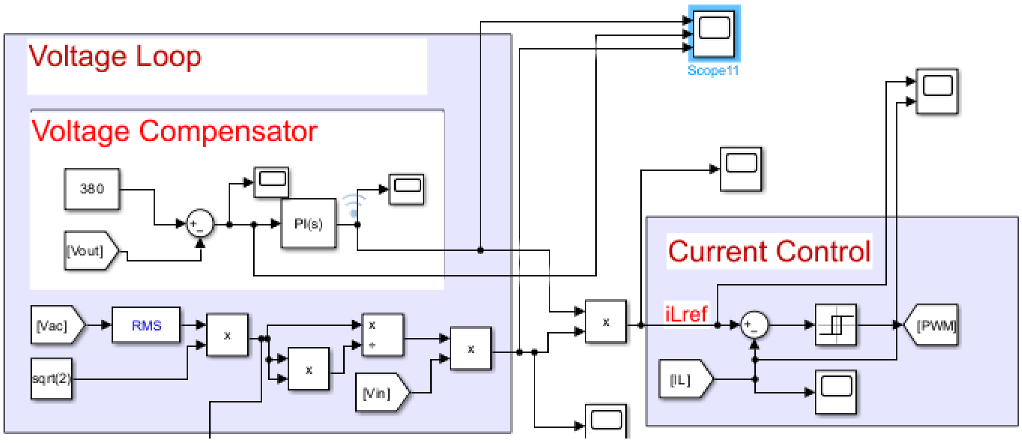

Figure 13: Control Circuit of the PFC Boost Converter

In this part, we need to achieve power factor correction, which means that there is no phase difference between the input voltage and input inductor current. Therefore, we need to control the waveform of the inductor current with the added voltage open loop. Meanwhile, we still need to keep the output voltage and power at a desired level.

The whole voltage outer loop can be composed of two parts: Voltage Compensator and Reference Waveform, which is the lower part shown in upper figure. This lower part outputs the waveform shown in Figure 14, which can provide the reference waveform shape for the inductor current.

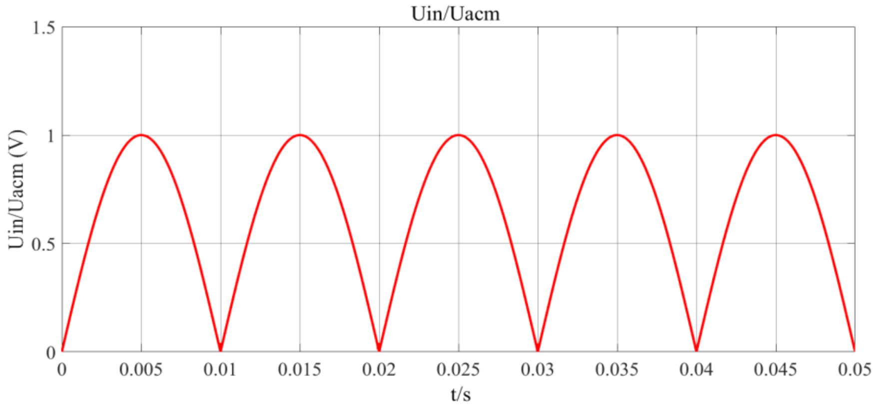

Figure 14: Output Waveform of Lower Part of Outer Voltage Loop

However, we need to know the magnitude of the reference current so that it can compare with the actual waveform of the inductor current. Consequently, this task can be done with voltage compensator. The voltage compensator originates from the output side of the power stage, then outputs the difference of the output voltage and reference value, namely output error to the PI block. The PI Block can adjust the error so that the reference waveform can be maintained, and the requirements of the output side can be satisfied.

4.3.2 PI Block

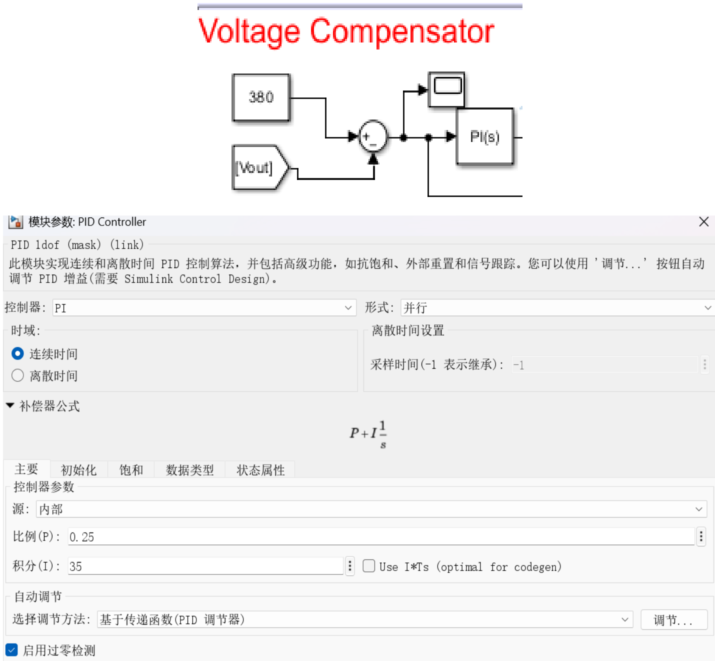

Figure 15: PI Block

After receiving the error signal from the output side, the PI regulator calculates the output signal through proportional and integral calculations. The proportional parameter Kp is used to adjust the output value; Integral parameters can amplify the error signal to offset the inevitable errors present in the system. In this way, the PI regulator can effectively reduce errors and improve system response speed.

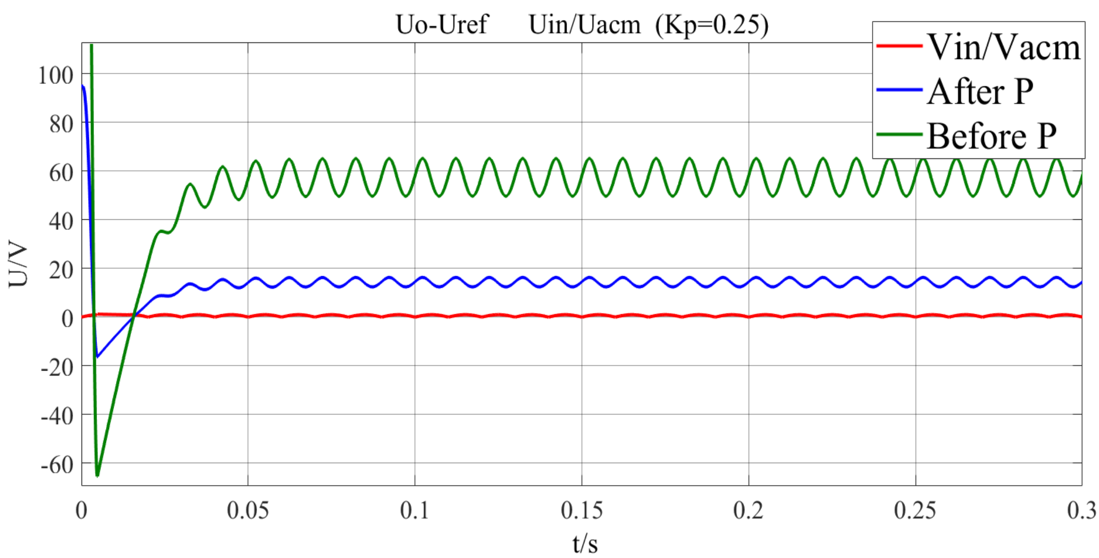

Figure 16: Error Signals with P Block (Kp<1)

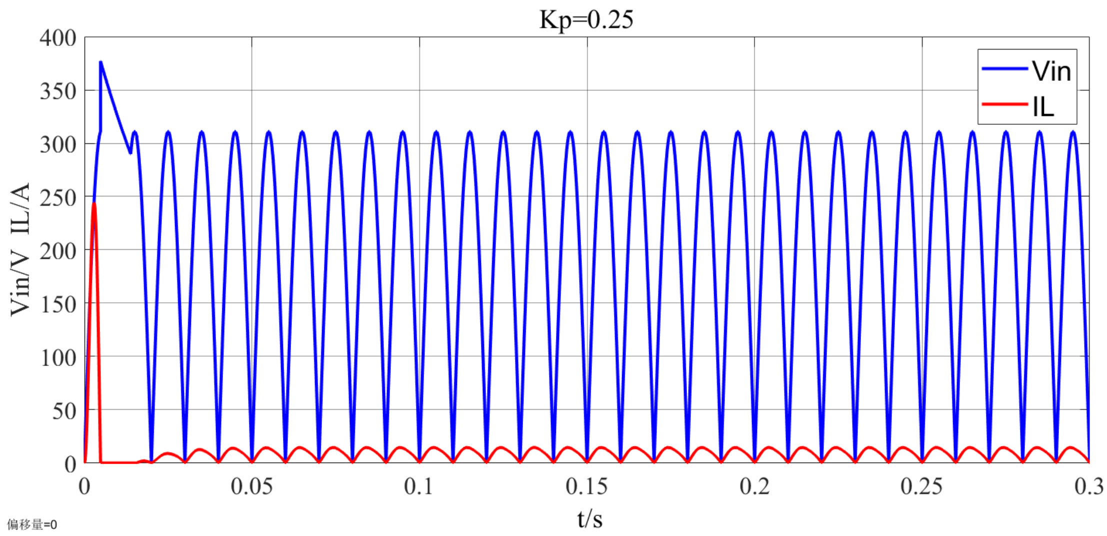

Figure 17: Inductor Current and Input DC Voltage with Kp=0.25

Figure 16 shows the waveform of voltage compensator block with Proportional Block when Kp is 0.25. As what has been shown, the green line shows the waveform before P block, which is also the difference between output voltage and reference value, namely output error here. The blue line shows the waveform going through P block.

We can see that with P block, the error can be reflected rapidly, and there is not much oscillation in the transient period. However, it can not eliminate the error thoroughly. It is obvious that the error of output voltage is somewhat too large, which can influence the output value. This is because Kp is smaller than 1.

When Kp is smaller than 1, the output error at steady state is enlarged. At the beginning of transient period, the output voltage is larger than 380 V, which means the output error is negative. At this period, the P block outputs the value larger than negative error so that the transient duration can be shortened. However, when the output voltage is smaller than reference value, the output error of P block is actually smaller than positive output error. In this manner, the output error can be enlarged.

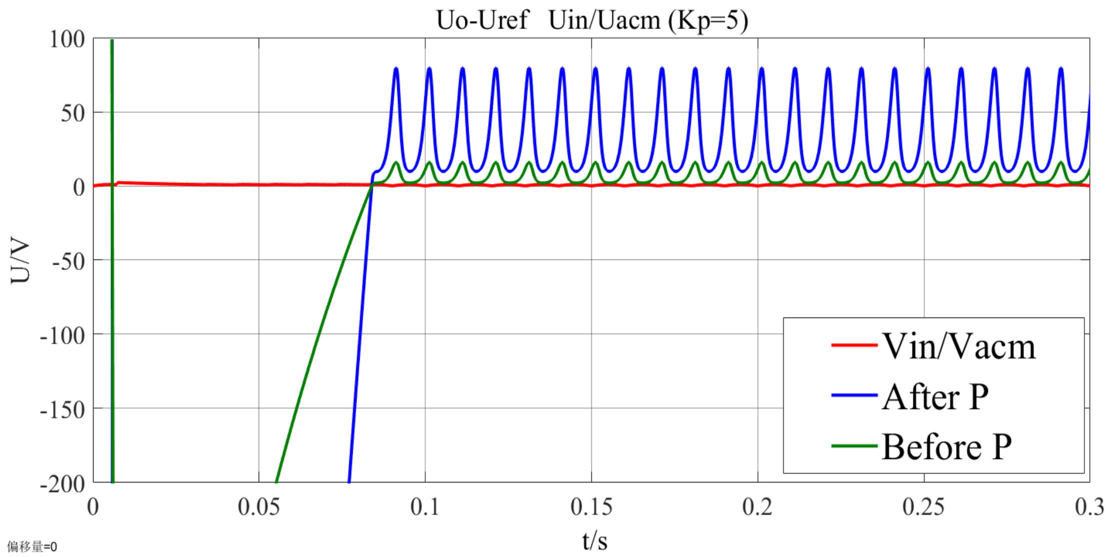

Figure 18: Error Signals with P Block (Kp>1)

Vice Versa, when Kp is larger than 1, the error is shortened. However, as shown in figure 19, the waveform of inductor current is not ideal. It is noticed that the steady-state error still can not be completely eliminated with only P block.

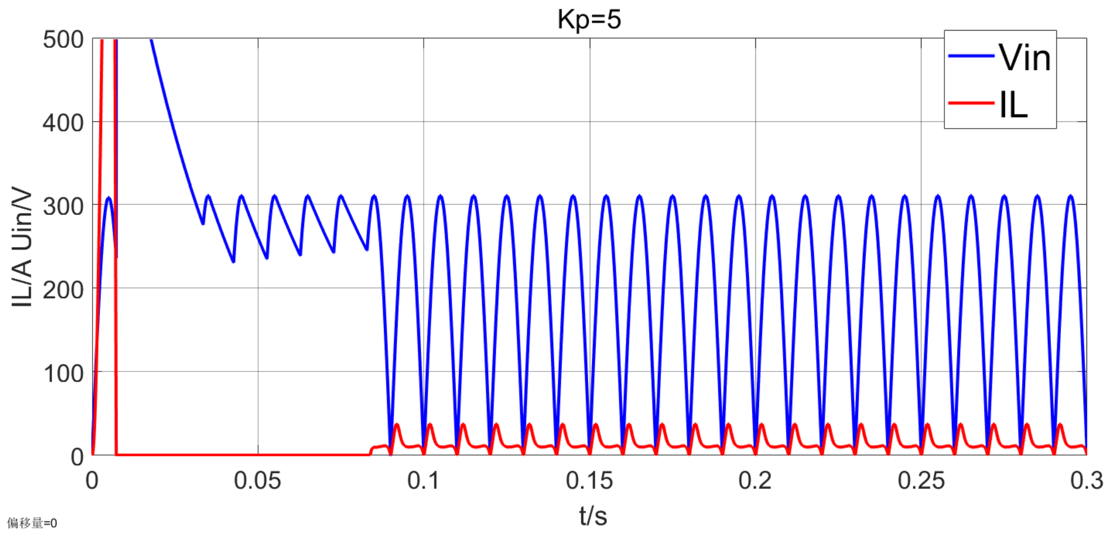

Figure 19: Inductor Current and Input DC Voltage with Kp=5

Therefore, it is not enough to only use P block. Then let’s see conditions with a single Integral Block:

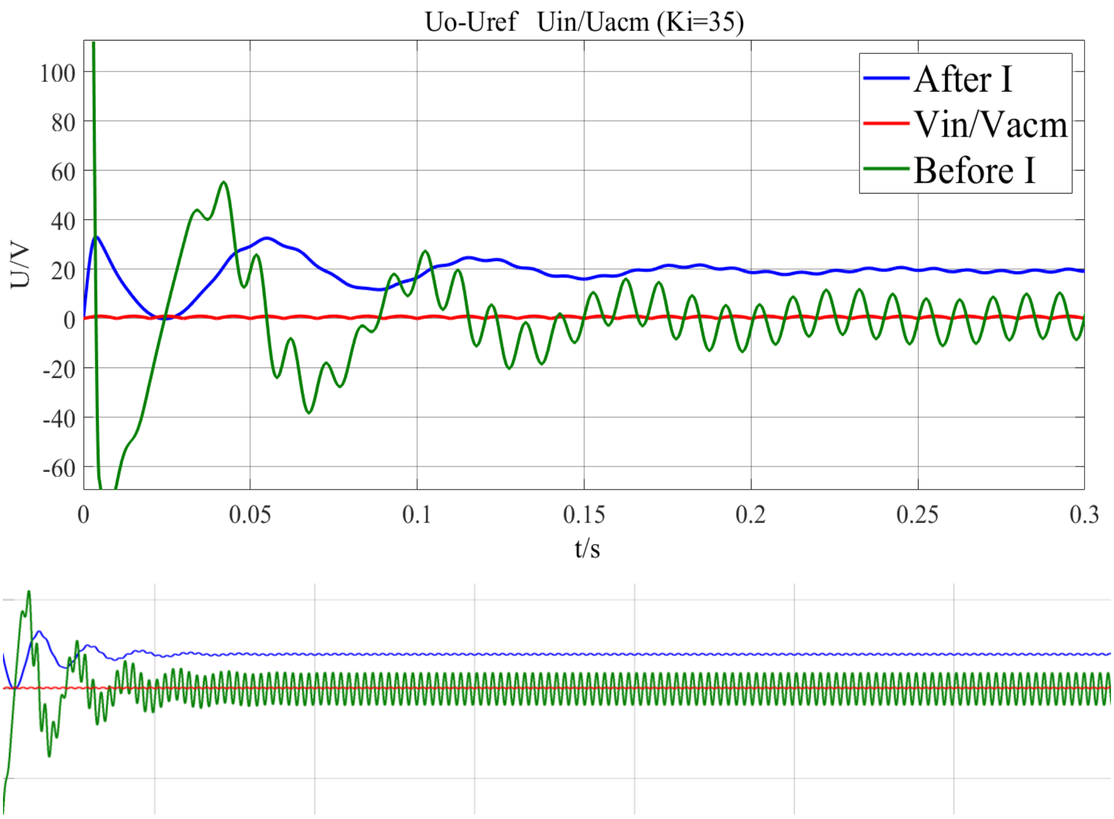

Figure 20: Error Signals with Integral Block

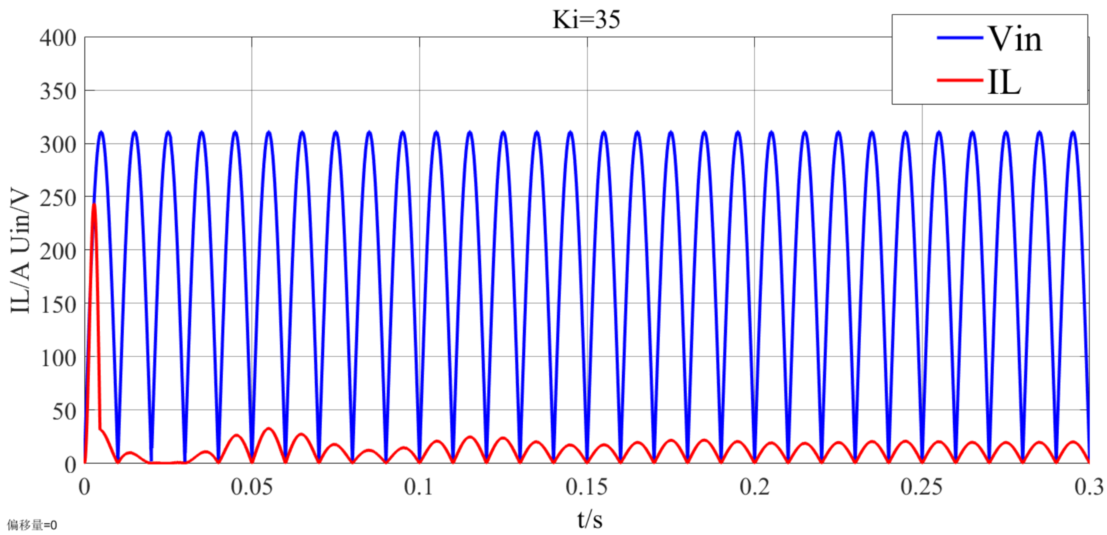

Figure 21: Inductor Current and Input DC Voltage with Ki=35

Figure 21 shows the waveform of voltage compensator with Integral Block when Ki is 35. Generally, it is set to eliminate steady-state errors. As long as there is an Error Integration Block in the system, it will continue to accumulate errors and output control variables to eliminate errors. If the error is zero, the integration will stop. However, if the integration effect is too strong (Ki is too large), it will increase overshoot and even cause the system to oscillate as shown in the transient period of figure 21.

Based on what has been mentioned above, we may combine the P and I to adjust the output error.

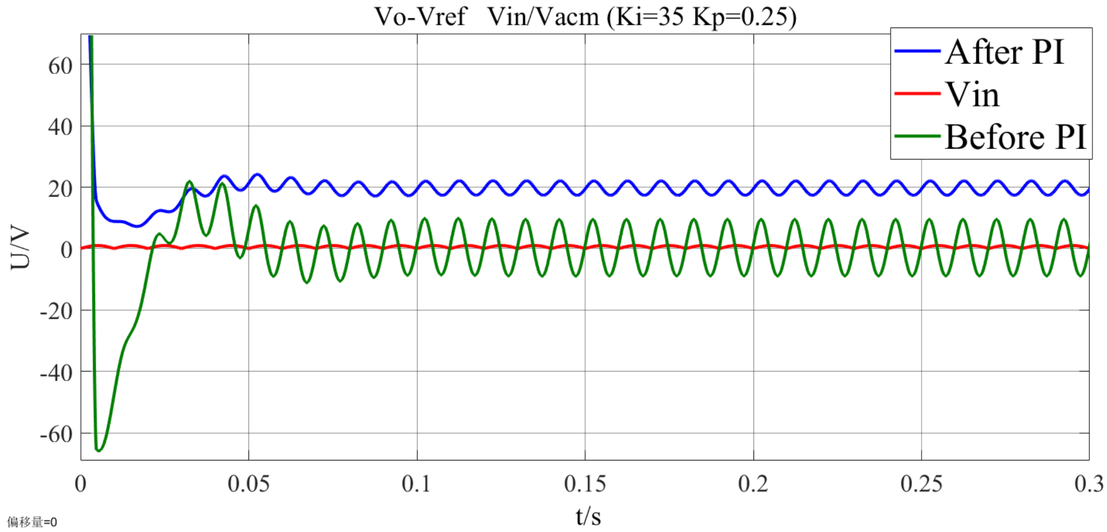

Figure 22: Error Signals with PI Block

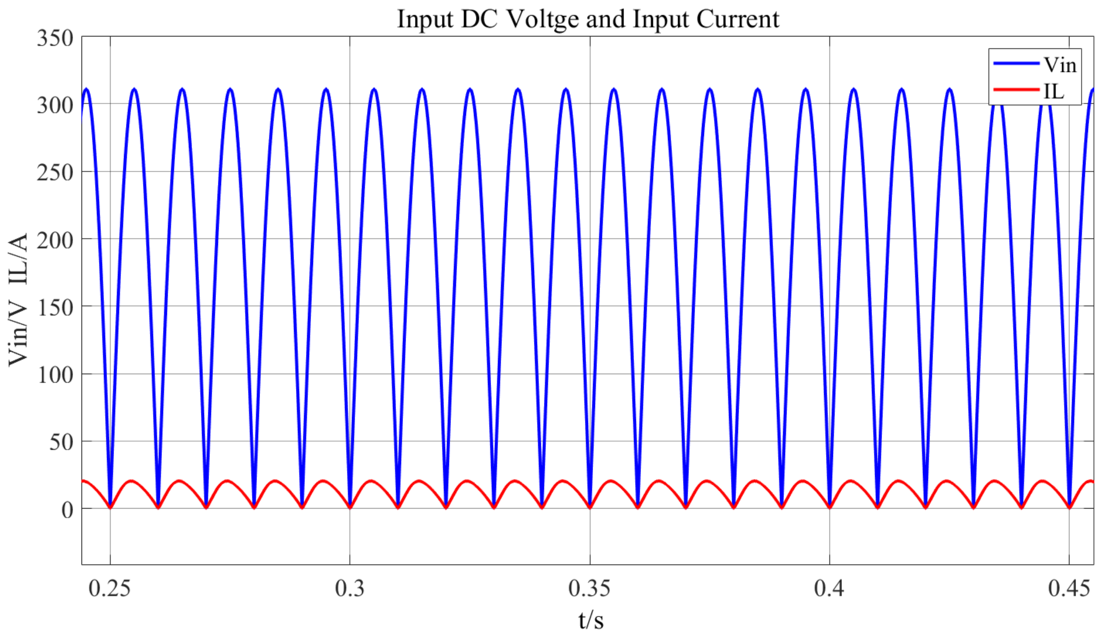

Figure 23: Inductor Current and Input DC Voltage with Ki=35, Kp=0.25

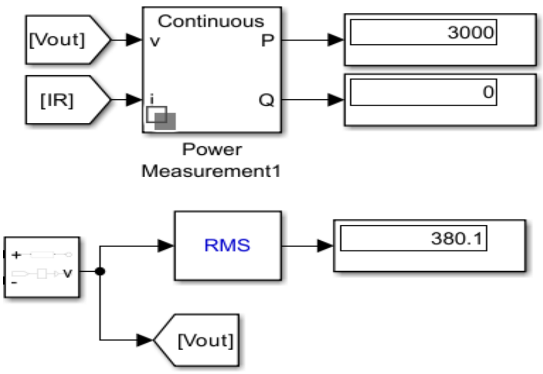

Figure 24: Output Result with Ki=35, Kp=0.25

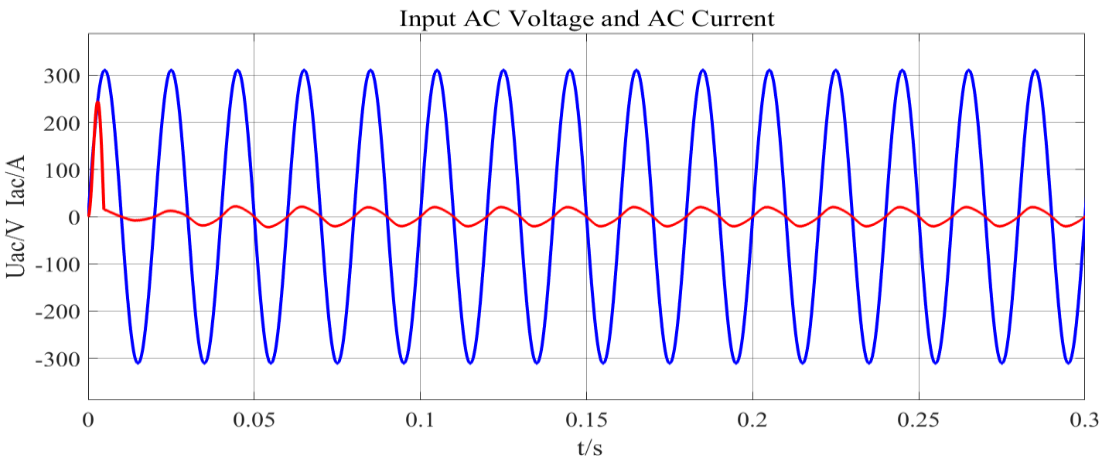

Figure 25: Input AC Current and AC Voltage

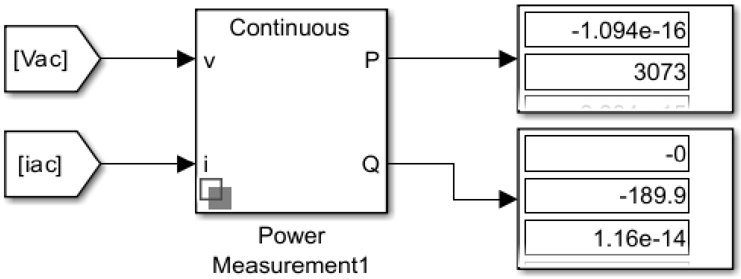

Figure 26: Power Measurement of AC Input Side

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \approx 0.998$$

From Figures above, we can see that everything goes well with PI Block: the transient duration is shortened, the oscillation is weakened, the input power factor is closer to 1, and the requirements of output voltage and power can be satisfied.