Seminar 5

Wang XingYi 2226215258

Topic 1

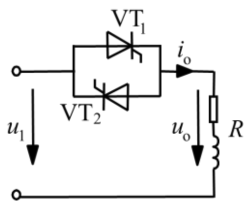
1. Topic

For topic 1, we need to analyze the AC voltage controller (phase control) with fixed load. To be more specific, we need to carry out three tasks:

1) Varying delay angle, observe output voltage waveform and input current waveform through simulation.
2) Study the relationships between the RMS value of output voltage and delay angle.
3) Study and verify the conditions of CCM.

2. Simulation Model

2.1 Simulation Schematic



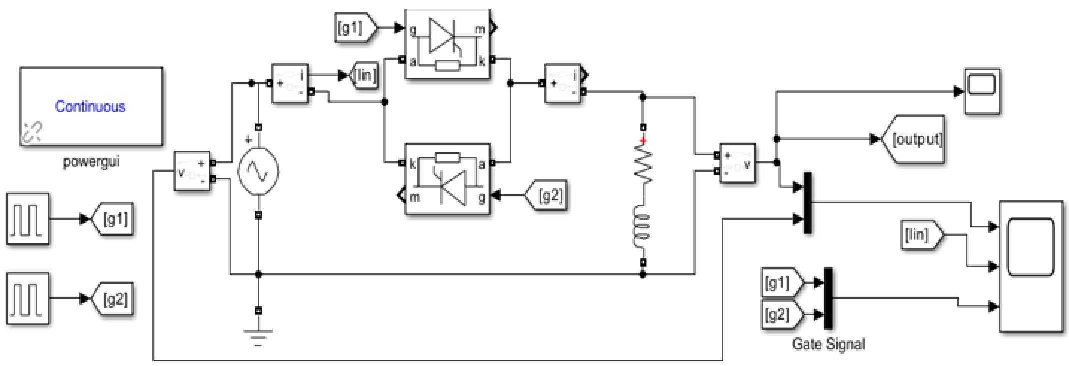


Figure 1: Simulation Model of AC Voltage Controller

Based on the circuit diagram, we established the model above so that we can observe the waveforms of pulse signals, input current, output voltage and analyze the harmonic components.

3. Parameter Setup

3.1 Major Parameter

Converter Type	Switch Type	Vin (RMS)	L	R
AC Voltage Controller	Thyristor	220V	22.3mH	10ohm

Based on the given parameters of load, we can calculate the impedance angle φ as:

$$\varphi = \arctan\left(\frac{\omega L}{R}\right) = \arctan(0.223\pi) \approx 35°$$

3.2 Device Parameter

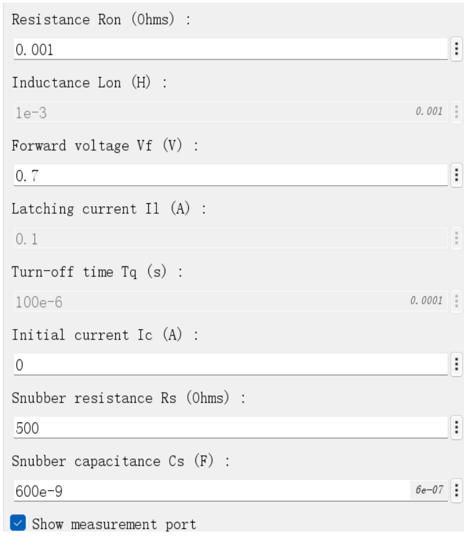


Figure 2: Parameters of switching thyristor

In this model, we assign snubber impedance for the switching thyristors to get smoother curves. Correspondingly, the waveform of output voltage will generate some kind of trivial oscillation, which is shown in figure 3. This phenomenon is caused by snubber capacitance and can be fixed by increasing the snubber resistance.

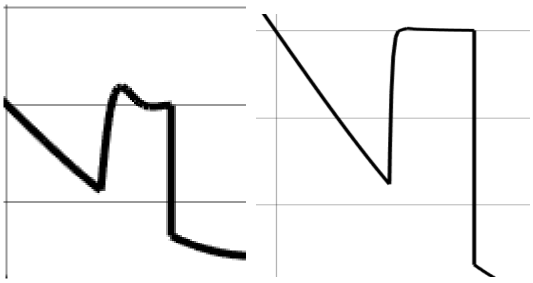


Figure 3: Waveform of output voltage when Cs=600e-9F, Rs=500ohm(L) Rs=1200ohm(R)

Figure 4: Parameters of Pulse Generator

For the pulse generator, we set the pulse width as 10 percent. We set ‘a’, which is a variable in the working zone, as the delayed angle, and two pulses have the phase difference which equals to 180 degrees.

3.3 MATLAB Program

In this topic, we need to analyze the output voltage and harmonic components with delay angle being variable. Thus, we need to write the MATLAB program below to acquire the desired data and plots.

```
   clc,clear
Uout = zeros(1,180);
U1out = zeros(1,180);
U3out = zeros(1,180);
U5out = zeros(1,180);
U7out = zeros(1,180);
U4out = zeros(1,180);
i=1;
for a = 1:1:180
    sim('M1.slx')
     Uout(i)=ans.Uo.Data(end);
     U1out(i)=ans.Uo1.Data(end);
     U3out(i)=ans.Uo3.Data(end);
     U4out(i)=ans.Uo4.Data(end);
     U5out(i)=ans.Uo5.Data(end);
     U7out(i)=ans.Uo7.Data(end);
      fprintf('循环第%d 轮\n',i);
      i=i+1;
end

alpha=1:1:180;
figure(1)
plot(alpha,Uout,'b-');
 xlabel('delay angle','fontname','times new roma');
 ylabel('RMS value of output voltage','fontname','times new roma');
  axis([0,180,0,inf]);
figure(2)
plot(alpha,U1out,'b-');
hold on
plot(alpha,U3out,'b-');
plot(alpha,U5out,'b-');
plot(alpha,U7out,'b-');
 xlabel('delay angle','fontname','times new roma');
 ylabel('Harmonic Component of Output Voltage','fontname','times new roma');
  axis([0,180,0,inf]);
figure(3)
plot(alpha,U3out,'b-');
 xlabel('delay angle','fontname','times new roma');
```

```
  ylabel('3rd Harmonic Component of Output Voltage','fontname','times new roma');
    axis([0,180,0,inf]);
figure(4)
plot(alpha,U5out,'b-');
  xlabel('delay angle','fontname','times new roma');
  ylabel('5th Harmonic Component of Output Voltage','fontname','times new roma');
    axis([0,180,0,inf]);
figure(5)
plot(alpha,U7out,'b-');
  xlabel('delay angle','fontname','times new roma');
  ylabel('7th Harmonic Component of Output Voltage','fontname','times new roma');
    axis([0,180,0,inf]);
figure(6)
plot(alpha,U4out,'b-');
  xlabel('delay angle','fontname','times new roma');
  ylabel('4th Harmonic Component of Output Voltage','fontname','times new roma');
    axis([0,180,0,inf]);
```

4. Simulation Results

4.1 Task one

Varying delay angle, observe output voltage waveform and input current waveform through simulation.

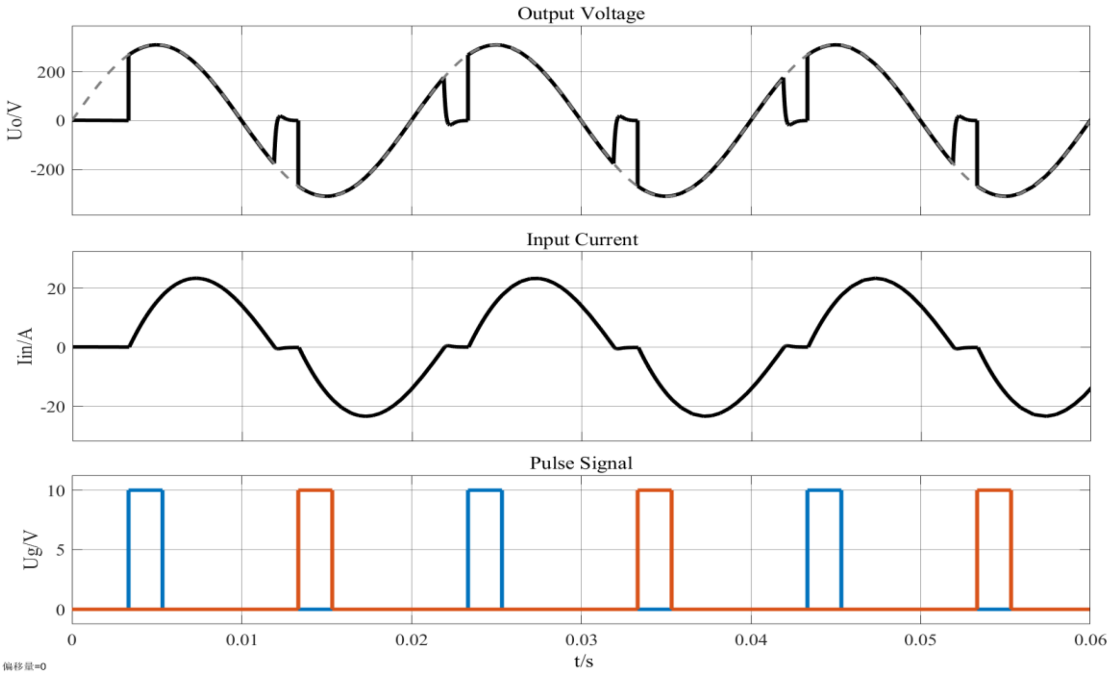


Figure 5: Waveforms of Uo, Iin, Pulse signals when α=60°

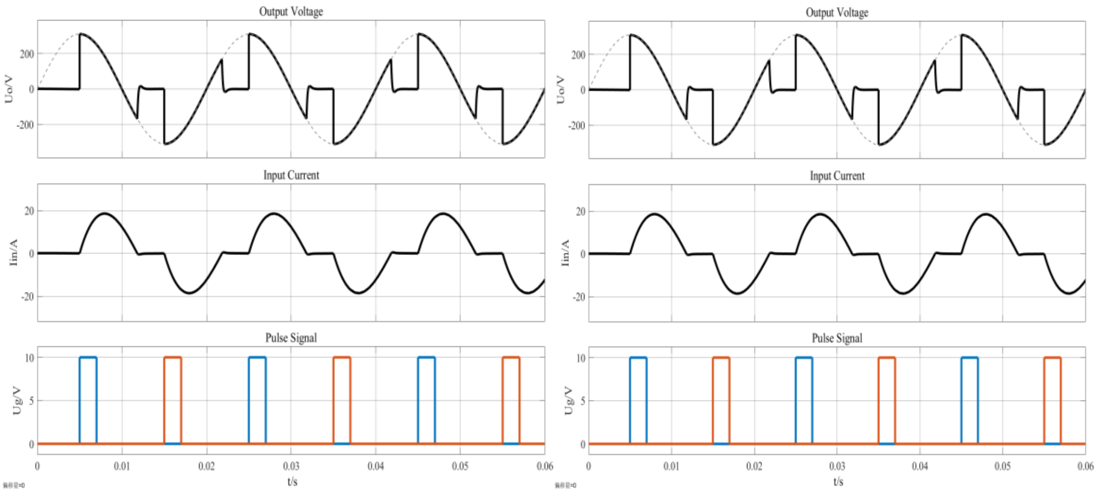


Figure 6: Waveforms of Uo, Iin, Pulse signals when α=90° (L)，120° (R)

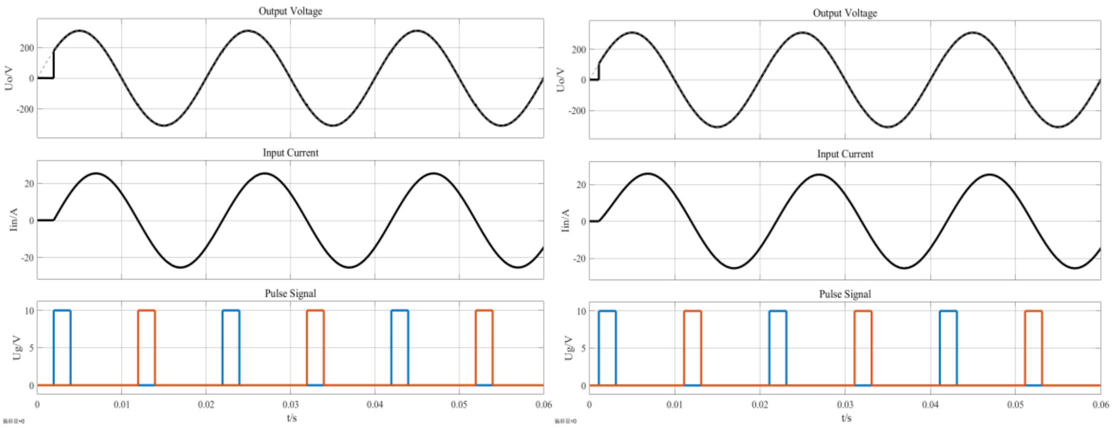


Figure 7: Waveforms of Uo, Iin, Pulse signals when α=35° （L)，20° (R)

$$\varphi = \arctan\left(\frac{\omega L}{R}\right) = \arctan(0.223\pi) \approx 35°$$

From Figure 5 and Figure 6, we can see that the waveform of output voltage and input current is discontinuous when $\alpha > \varphi$. The discontinuous duration increases with the increment of delay angle.

However, when $\alpha < \varphi$, we can see that the waveform is continuous in Figure 7.

4.2 Task Two

Study the relationships between the RMS value of output voltage and delay angle.

4.2.1 RMS Value of Output Voltage

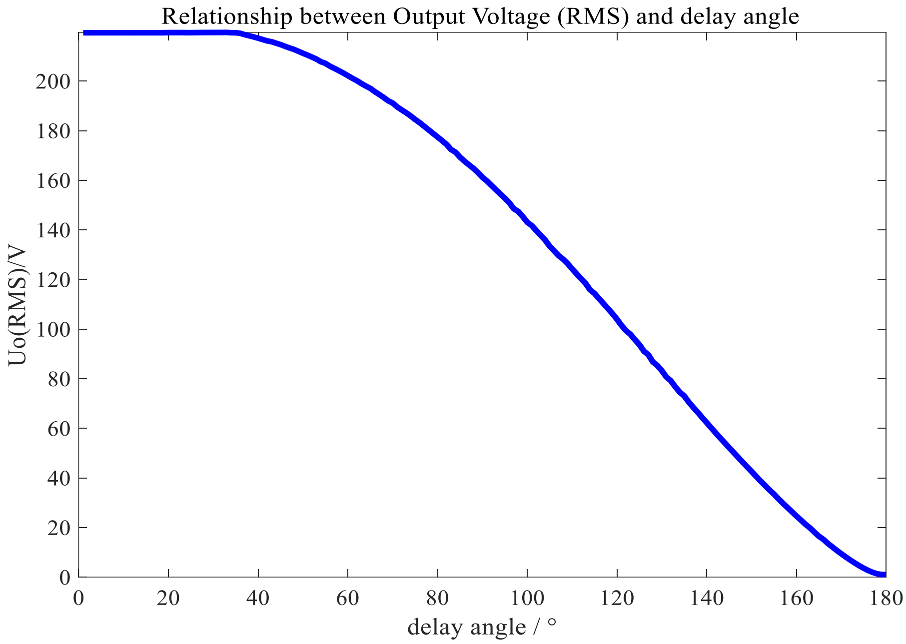


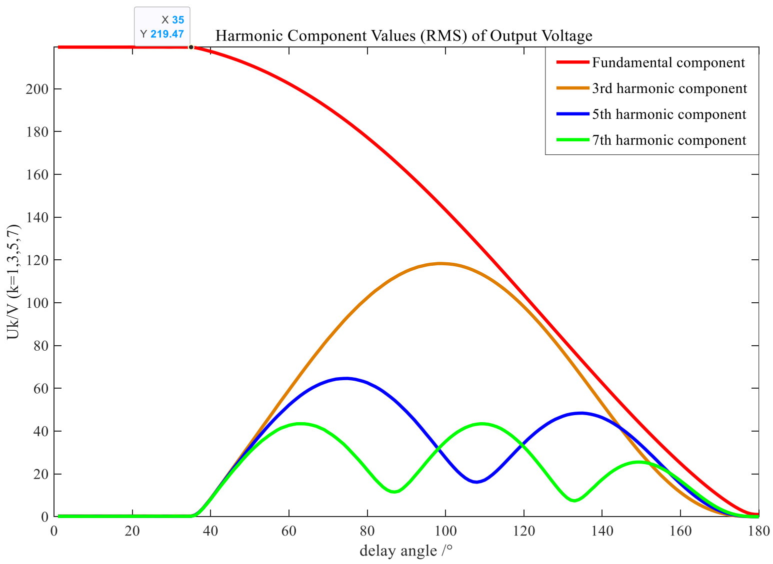
Figure 8: Uo (RMS)=f(α)

$$U_o = U_I \sqrt{\frac{\theta}{\pi} + \frac{1}{2\pi}\left[\sin 2\alpha - \sin(2\alpha + 2\theta)\right]}$$

$$\sin(\alpha + \theta - \varphi) = \sin(\alpha - \varphi) e^{\frac{-\theta}{\tan\varphi}}$$

When $\alpha < \varphi$, the effective value of output voltage is approximately equal to the effective value of grid voltage, which equals to 220V. When $\alpha > \varphi$, there is an intermittent period of output voltage, which becomes longer as delay angle increases. Therefore, the output voltage will gradually decrease. The detailed process can be explained through the formulas above. When the delay angle is approaching 180 degrees, there is no conducting period for the thyristors. Thus, the output voltage is 0V.

4.2.2 Harmonic Component



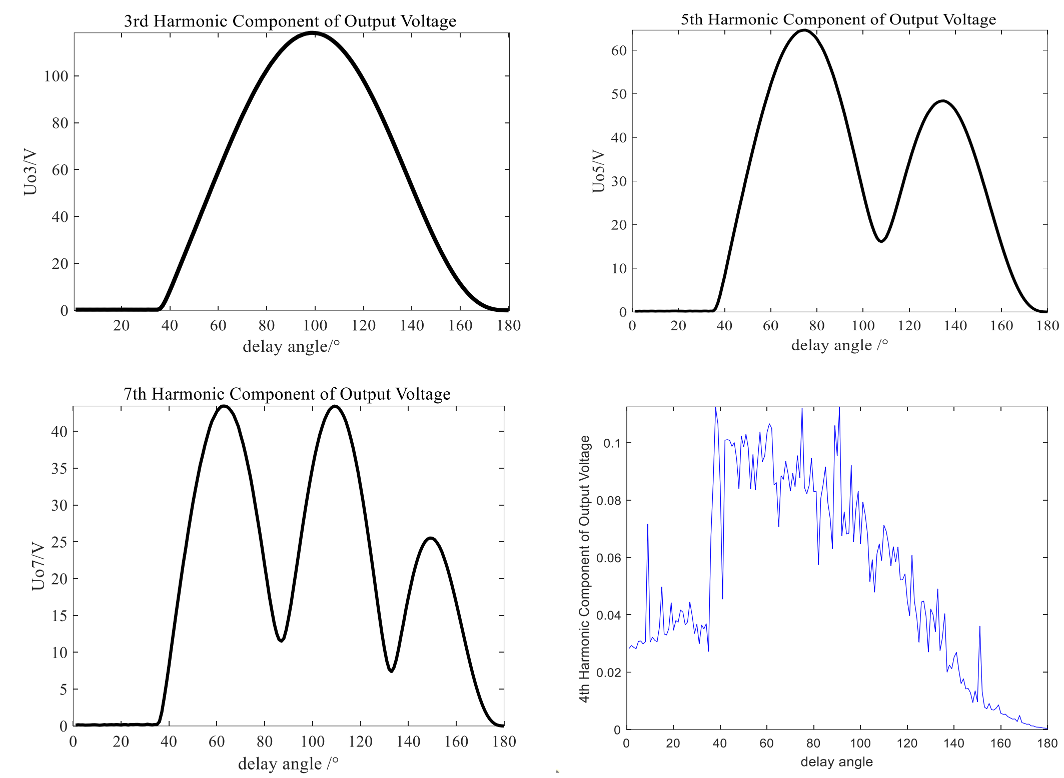


Figure 9: Harmonic waveforms of output voltage in AC voltage controller

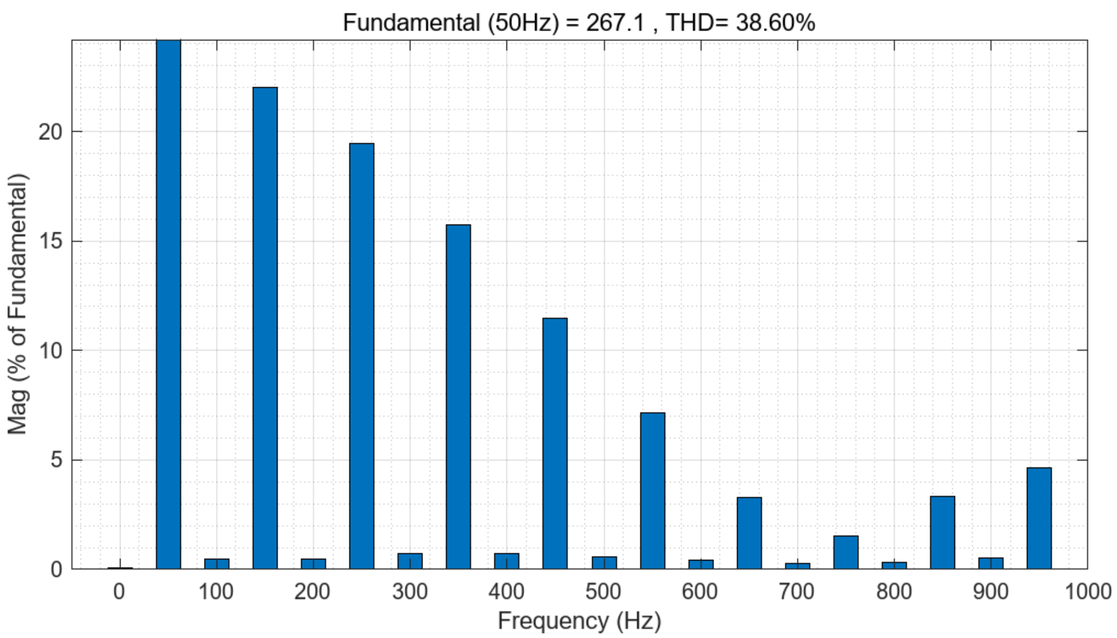


Figure 10: FFT analysis of AC voltage controller when $\alpha = 60°$

From the FFT analysis, we can see that there are almost no even orders of harmonic components for the waveform of output voltage is symmetrical about the x-axis. Only odd harmonics exist and the magnitude of the harmonic component decreases when the order increases.

This part will be thoroughly illustrated in Question 3.

4.3 *Task three*

Study and verify the conditions of CCM.

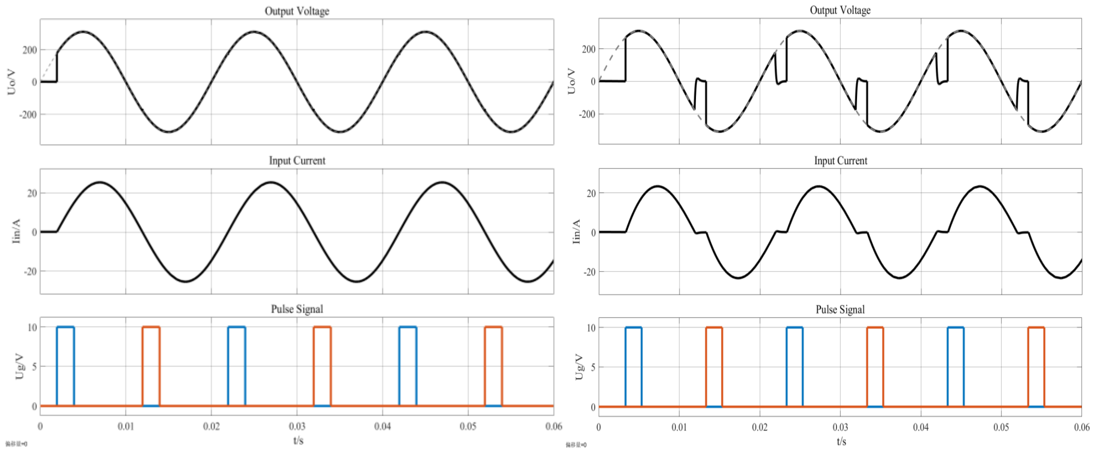


Figure 11: Waveform when $\alpha = 35°$ (L), $\alpha = 60°$ (R)

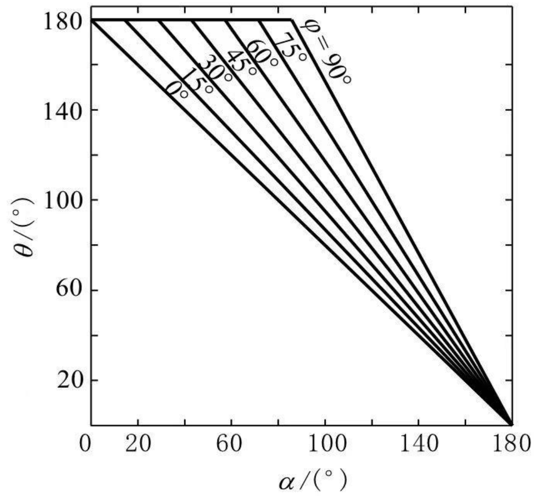


Figure 12: $\theta = f(\varphi, \alpha)$

$$\sin(\alpha + \theta - \varphi) = \sin(\alpha - \varphi) e^{\frac{-\theta}{\tan\varphi}}$$

Based on the transcendental equation above, we can get figure 12. When $\varphi < \alpha < \pi$, the conducting angle θ of both VT1 and VT2 is smaller than 180 degrees, which proves the existence of discontinuous period. When $\alpha < \varphi$, the thyristor will be triggered before the zero-crossing point of current. Thus, the current is still continuous. But it is noticed that there is a short start-up transient process for the output current. The exponential decay component of output current will cause the longer conducting time for VT1 and shorter time for VT2 initially. After a short period of time, the conducting angle of VT1 and VT2 will be the same. Consequently, we can sum that the CCM criterion for AC-AC voltage controller is that:

$$0 < \alpha \leqslant \varphi$$

Where φ is the impedance angle of the load.

Topic 2

1. Topic

For Topic 2, we need to analyze an AC chopper with the same load and input voltage as Topic 1. In this part, we need to tackle three questions:

1) Varying **duty cycle**, simulate to observe **output voltage waveform** and **input current waveform** with grid voltage as reference
2) Analyze ***commutation process***
3) Study the relationships between the **RMS value of output voltage** and **duty cycle**

2. Simulation Model

2.1 Simulation Schematic

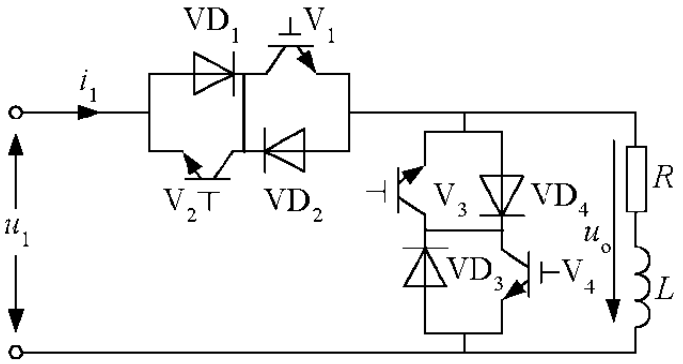


Figure 13: AC voltage Chopper

From Figure 13, we can see that VD1 and VD2 can be connected, so do VD3 and VD4. Therefore, we build up our simulation model as shown in Figure 14. What's more, because the voltage in this topic is not too large for IGBT to endure, the anti-series resistors do not need to be so large.

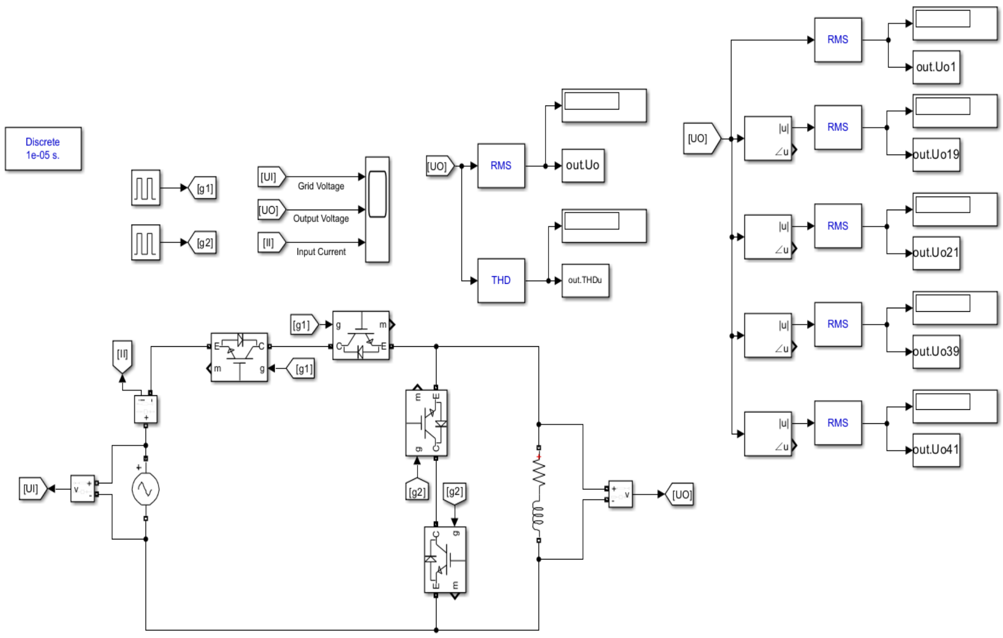


Figure 14: Simulation Model of AC voltage Chopper

3. Parameter Setup

3.1 Major Parameter

Converter Type	Switch Type	Vin (RMS)	L	R	fs
AC Voltage Chopper	IGBT	220V	22.3mH	10ohm	1000Hz

'fs' in the table above refers to the frequency of gate signals from two pulse generators in Figure 13.

3.2 Device Parameter

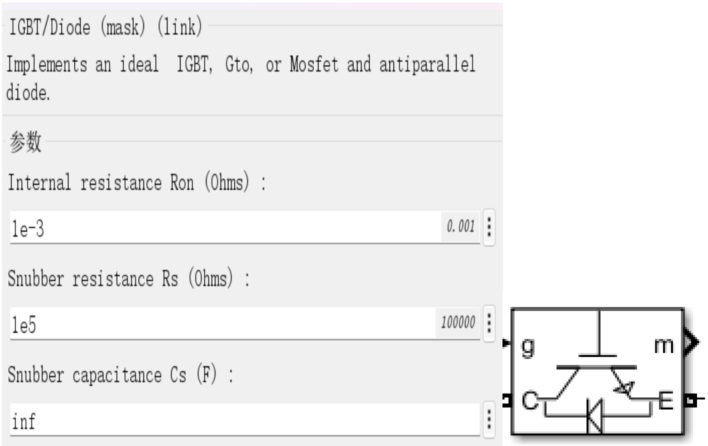


Figure 15: Simulation Model of AC voltage Chopper

Figure 16: Simulation Model of AC voltage Chopper

The conducting sequence of upper two IGBTs is totally the same, which also applies to the lower two IGBTs. It is noticed that the triggering signals of upper switches are totally complementary to the lower signals, which can be seen in Figure 16.

3.3 MATLAB Program

```
%% 谐波分析
clc;clear;
```

```
N=99;k=1;
Uo1=zeros(1,N);
Uo19=zeros(1,N);
Uo21=zeros(1,N);
Uo39=zeros(1,N);
Uo41=zeros(1,N);
THDu=zeros(1,N);

tic %计时模块
for D=1:1:99
    out=sim('AC_chopper',[0,0.05]);
    Uo1(k)=out.Uo1.Data(end);
    Uo19(k)=out.Uo19.Data(end);
    Uo21(k)=out.Uo21.Data(end);
    Uo39(k)=out.Uo39.Data(end);
    Uo41(k)=out.Uo41.Data(end);
    THDu(k)=out.THDu.Data(end);
    fprintf('第%d 轮\n',k);
    k=k+1;
end
toc

clf;

d=1:1:99;
figure(1)
plot(Uo1,THDu,'b-');
xlabel('$U_{o1}/ \mathrm{V}$','Interpreter','latex','fontname','times new roma');
ylabel('THDu','Interpreter','latex','fontname','times new roma');
title('THDu=f(Uo1)','Interpreter','latex','fontname','times new roma');

figure(2)
plot(d,Uo1,'k-');
hold on
plot(d,Uo21,'b-');
plot(d,Uo41,'m-');
xlabel('D/ \%','Interpreter','latex','fontname','times new roma');
ylabel('Harmonic Component of Output Voltage/$\mathrm{V}$','Interpreter','latex','fontname','times new roma');
legend('1st','19th and 21st','39th and 41st','Interpreter','latex','fontname','times new roma');
```

4. Simulation Results

4.1 *Task one*

Varying **duty cycle**, simulate to observe **output voltage waveform** and **input current waveform** with grid voltage as reference

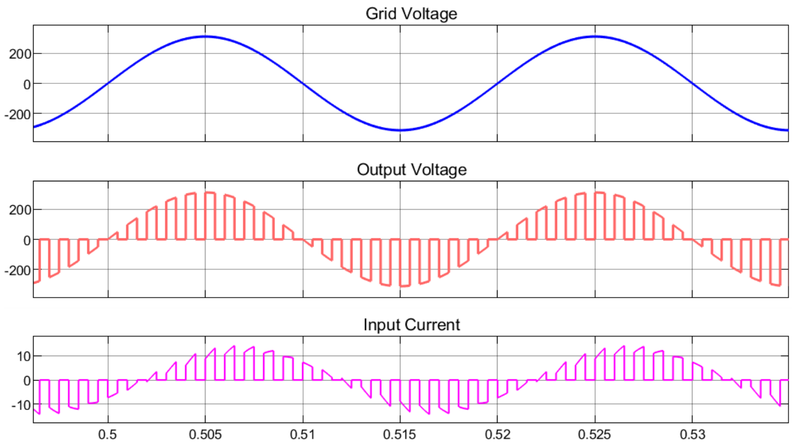


Figure 17: Waveforms of Uin, Uo and Iin when Duty Cycle =25%

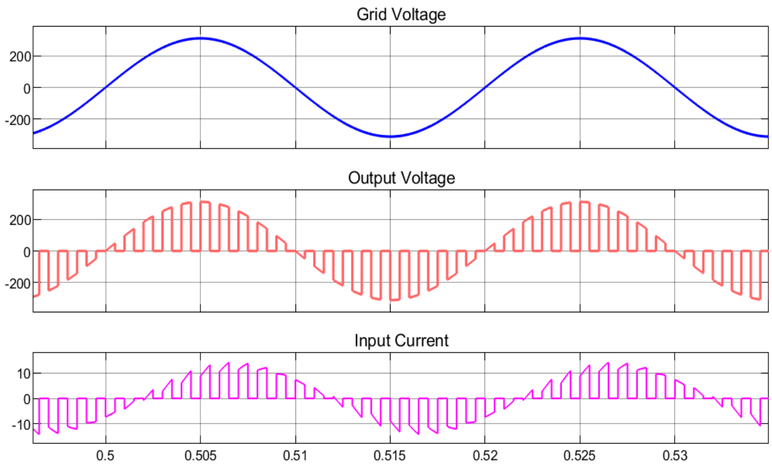


Figure 18: Waveforms of Uin, Uo and Iin when Duty Cycle =50%

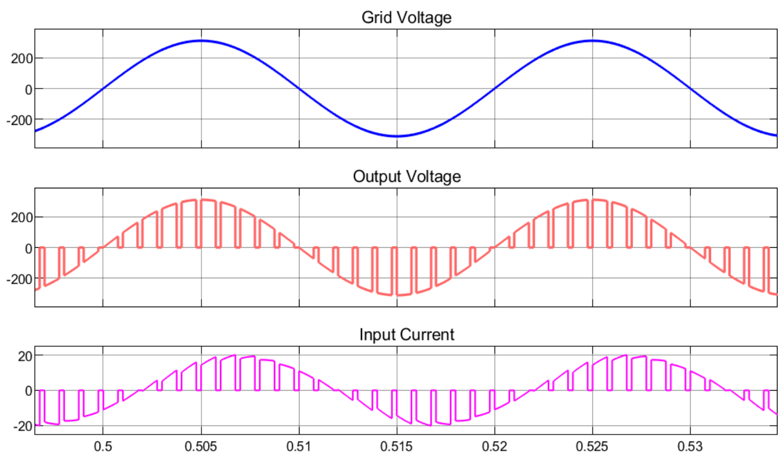


Figure 19: Waveforms of Uin, Uo and Iin when Duty Cycle =75%

4.2 *Task two*

Analyze ***commutation process***

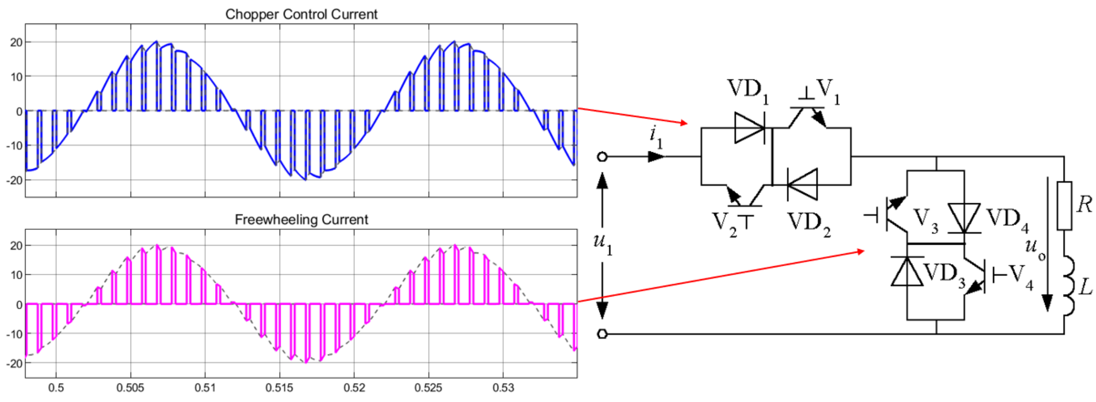


Figure 20: Waveforms of current when Duty Cycle =75%

From Figure 20, we can see the waveform of chopper control current and freewheeling current. Based on the KCL, we can know the contour of these two current forms the output current waveform. So the conducting path is mainly determined by the polar of output current and conducting IGBTs. The detailed commutation process is listed below:

Polar of Ui, Io	When V1,V2 on	When V3,V4 on
ui>0,io>0	V1(charging)	V3 (freewheeling)
ui>0,io<0	V2(energy feedback)	V4(charging)
ui<0,io>0	V1(energy feedback)	V3(charging)
ui<0,io<0	V2(charging)	V4(freewheeling)

4.3 *Task three*

Study the relationships between the **RMS value of output voltage** and **duty cycle**

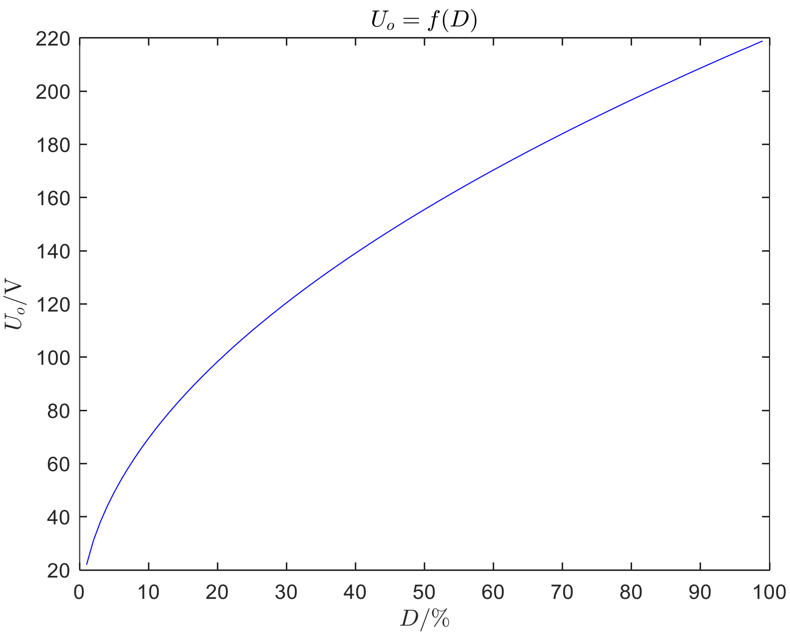


Figure 21: Uo (RMS)=f(D)

From Figure 21, we can see that the output voltage becomes larger and larger as Duty Cycle increases, approaching the grid voltage finally.

Topic 3

1. Topic

Given that the above two converters share ***the same fundamental component of output voltage***, compare and analyze the differences of output voltage's harmonic components.

2. Harmonic Components

2.1 AC Voltage Controller (phase control)

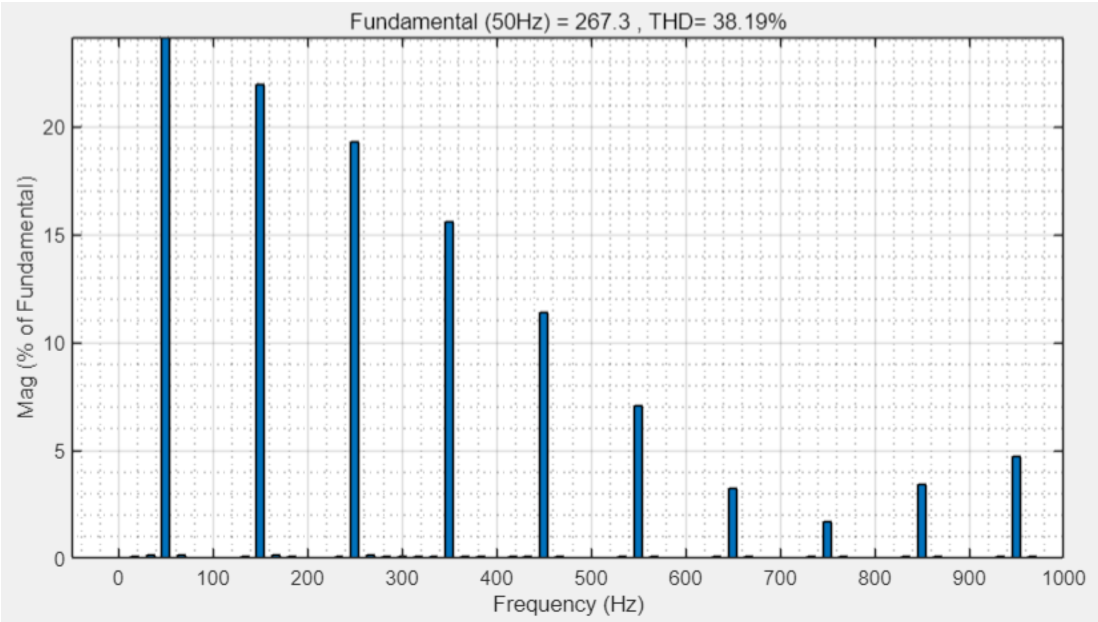


Figure 22: FFT analysis of AC Voltage Controller when delay angle is 60 degrees

From Figure 22, we can see that there are only odd numbers harmonic components. There is almost no even harmonic component of output voltage.

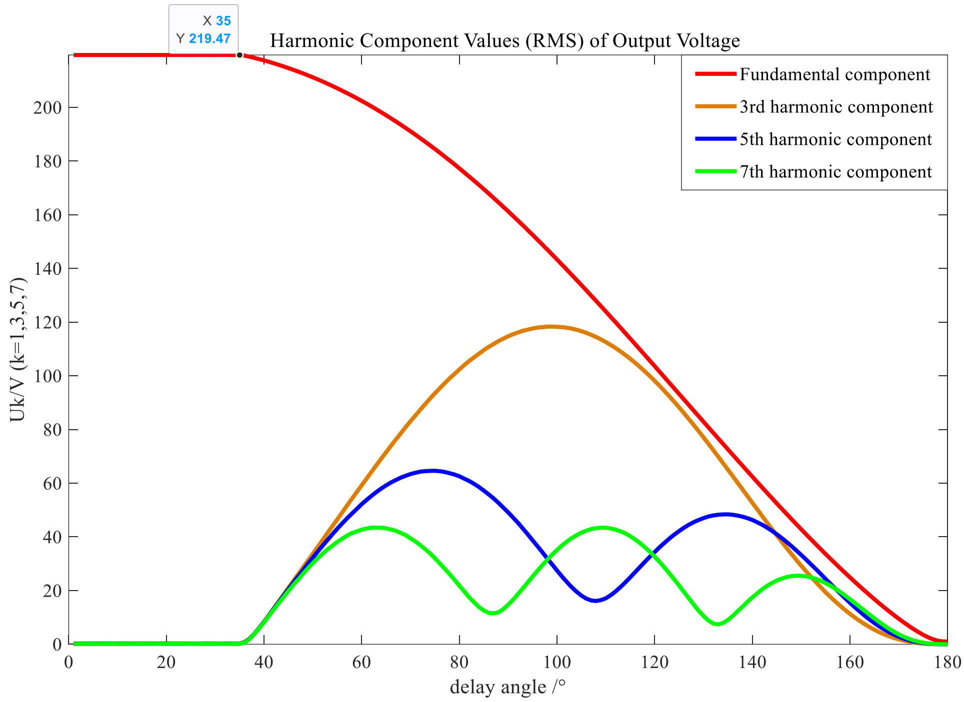


Figure 23: Relationships between different harmonic components and delay angle

From Figure 23, we can see that the delay angle can affect the magnitude of different harmonic components, this can correspond to the Figure 23 where delay angle equals to 60 degrees.

2.2 AC Chopper

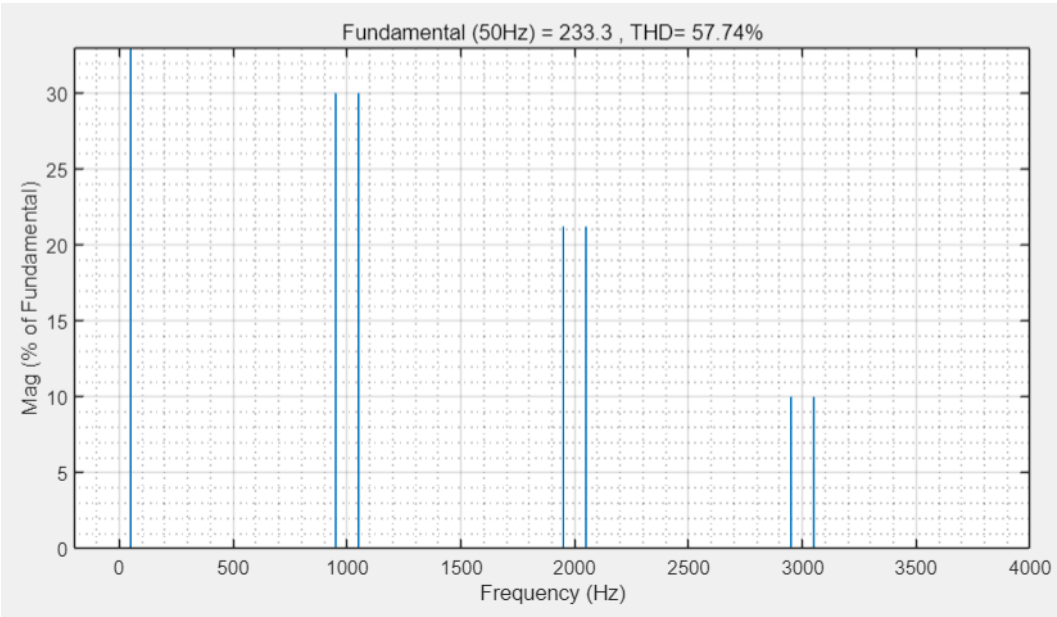


Figure 24: FFT analysis of AC Chopper when Duty Cycle is 50%

However, for AC Chopper, there only exist the fundamental component and $20k \pm 1$ ($k = 1, 2, 3 \ldots$) orders of harmonic components. It is noticed that there is still no even harmonic component.

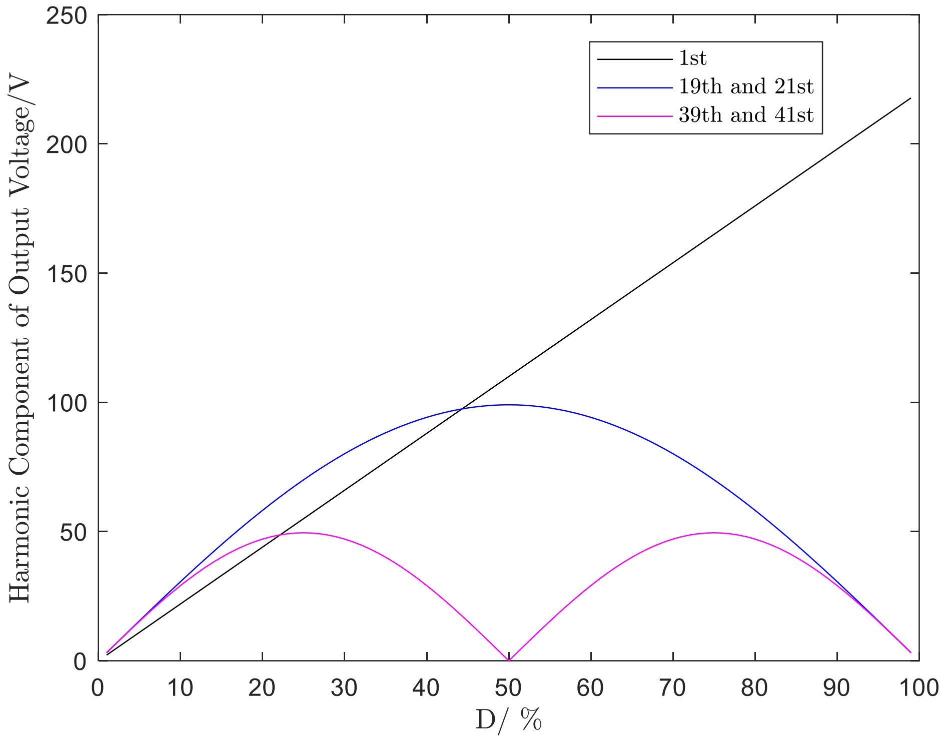


Figure 25: Relationships between different harmonic components and Duty Cycle

Like AC voltage Controller, different harmonic components can also be influenced by Duty Cycle.

2.3 Comparison of Two Converters

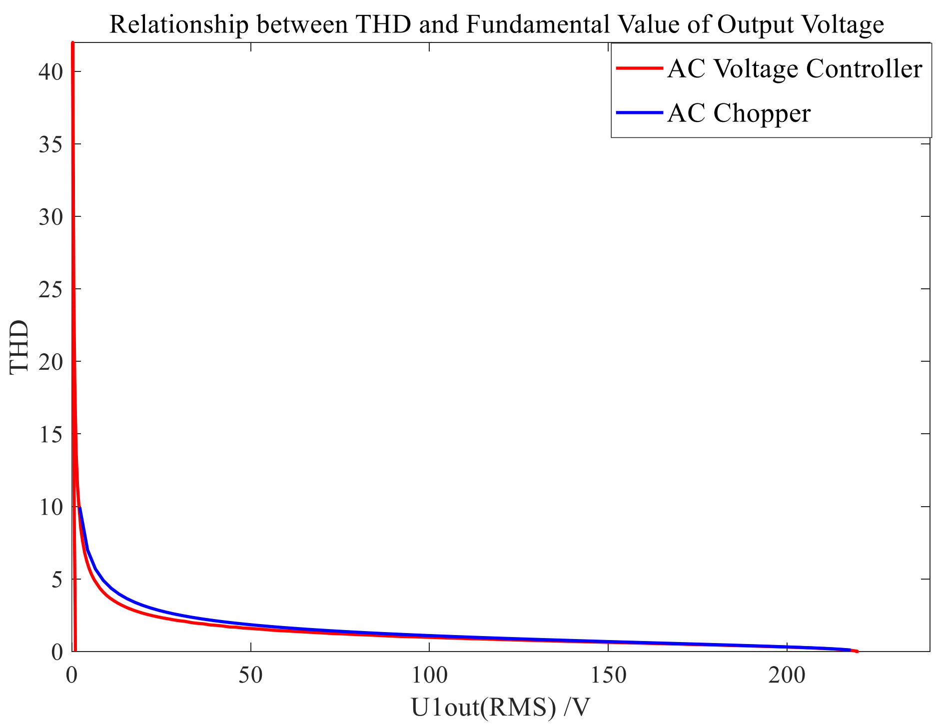


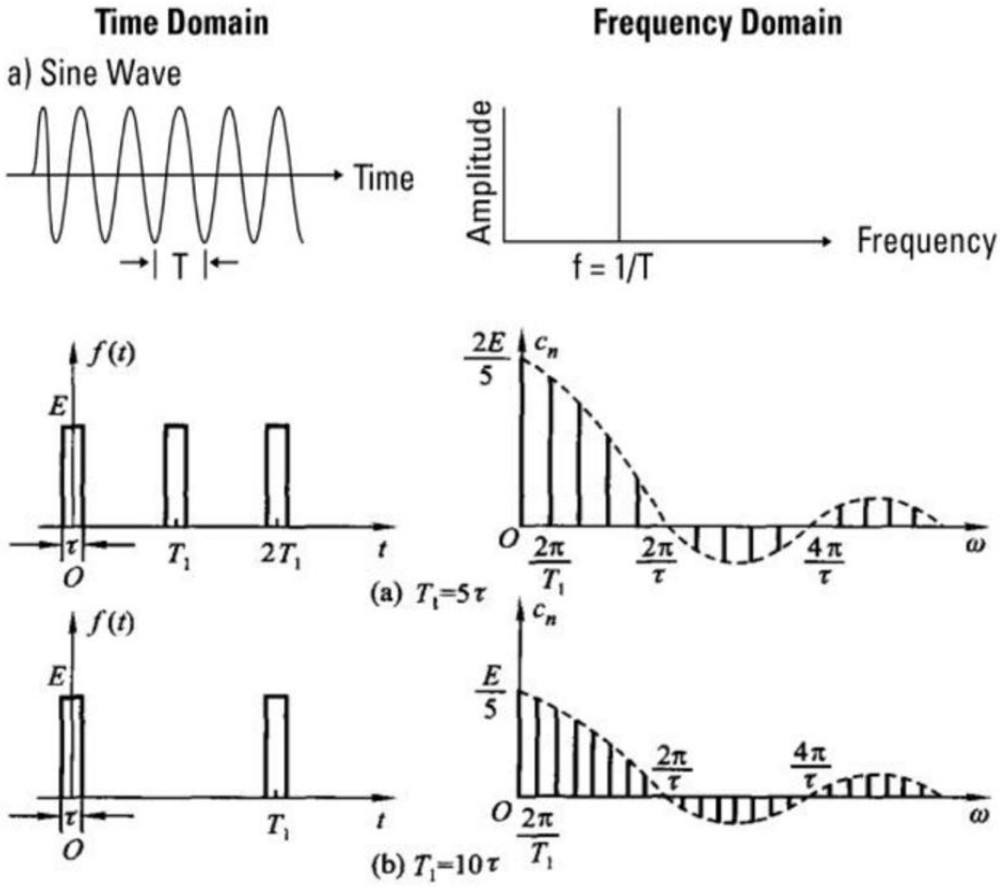
Figure 26: Relationships between THD and fundamental component of output voltage

To make comparisons between harmonic values of two converters, we generate the plots between THD and the RMS value of fundamental output voltage component. With the same value of output voltage, we can compare the THD of these two converters. From Figure 26, we can see that there is larger THD for AC chopper. Nevertheless, although the chopper control circuit has larger harmonics, the harmonics it contains are all high-order, which can be easily removed by passive filters. Therefore, in practical applications, chopper control circuits perform better.

3. Analysis of Results

Actually, the output voltage of both two converters can be seen as the product of sinusoidal wave and a rectangular wave.

The difference is that the frequency of rectangular wave of AC voltage controller is the same as line frequency, which equals to 50Hz. But the frequency of rectangular wave of AC Chopper is the frequency of gate signals, which is 1000Hz in our group.



To analysis the harmonic components of output voltage, we can do convolution integral of these two signals in frequency domain. Because the sinusoidal wave corresponds to a pulse signal in frequency domain, we can just let this pulse "scan" the rectangular wave in frequency domain when doing **convolution integral**. For AC chopper, the frequency of switch(1000Hz) is way larger than line frequency (50 Hz). So there only exist line frequency component and harmonic based on switching frequency. When you change the delay angle and duty cycle of these two converters, you simultaneously change the pulse width of rectangular wave, which can directly affect the density of the wave in frequency domain. Furthermore, while doing convolution integrals, the harmonic components of output voltage can be changed.

Besides, we can see both two converters output voltage can satisfy with:

$$f(t) = -f\left(t \pm \frac{T}{2}\right)$$

Which indicates that the output voltage of both two converters is an odd harmonic function. There is just no even harmonic components for an odd harmonic function.