Seminar 3

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Topic 1

1. Topic

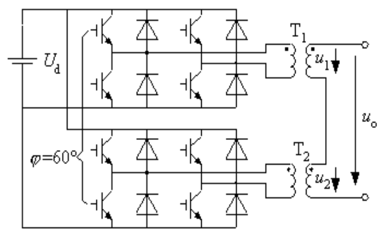
This topic contains three major tasks on the series connection of 2 single-phase VSIs with single-phase full-bridge inverter. We can adjust the waveform of output voltage by changing the phase angle, so we build up the following model.

2. Simulation Model

To be more specific, we are required to use 180° conducting mode ($\theta = 180°$) and change the external phase-shifting angle φ between two invertors. Here are the tasks we need to tackle.

1) Observe the single invertor's time sequence waveform and input/output voltage relationships with 180° conducting mode.
2) Study the basic operating principle of series connection of multiple single-phase VSIs.
3) With external phase-shifting angle φ varying, we need to plot the curves characterizing the relationship between φ and RMS value of the fundamental component in output voltage,3rd 5th 6th 7th and 9th harmonics components, THD of output voltage.

2.1 Circuit Schematic



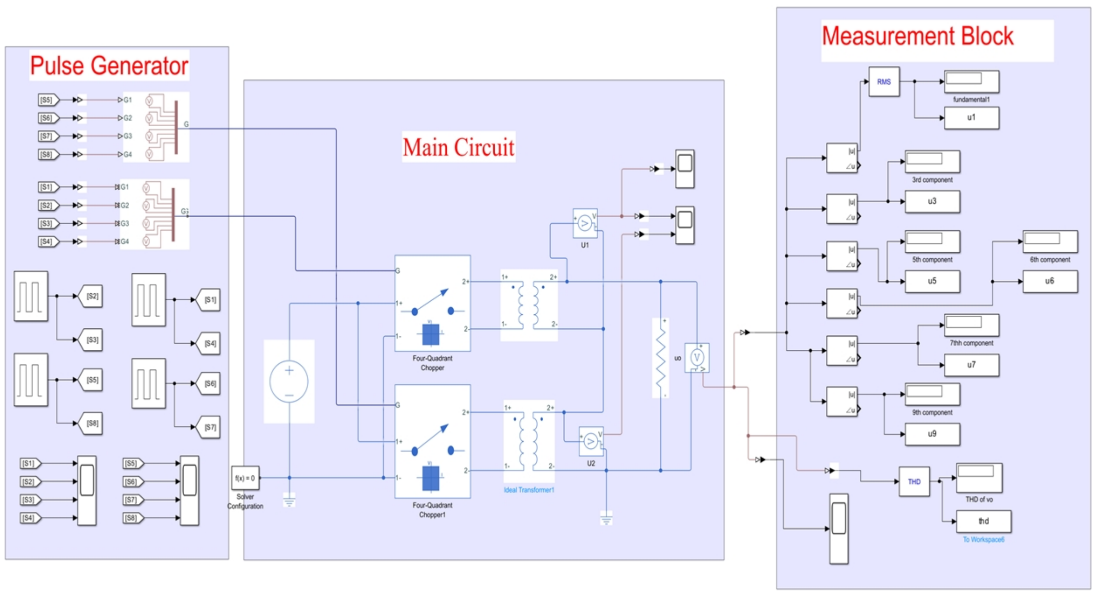


Figure 1: Simulation model 1

The model above is composed of three major parts: Main Circuit, Pulse Generator, Measurement Block.

2.2 Main Circuit

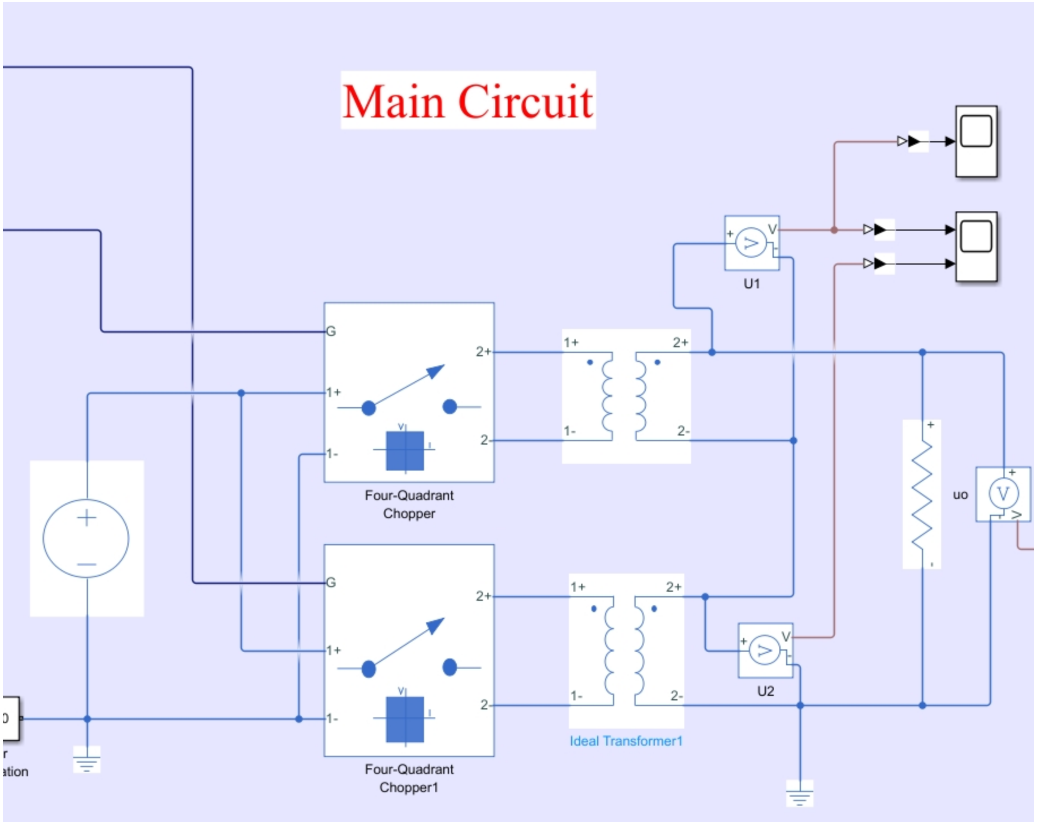
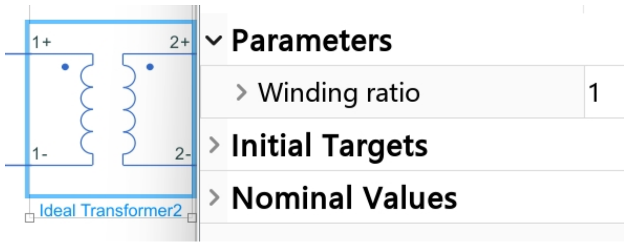


Figure 2: Main Circuit



The winding ratio of the transformer is set to be 1.

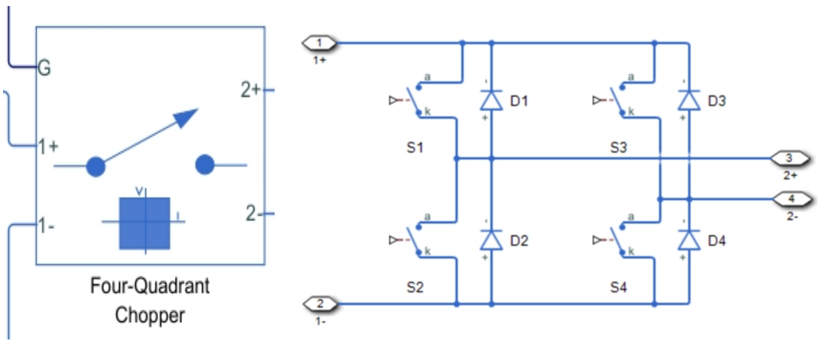


Figure 3: Four-Quadrant Chopper and its equivalent circuit

In the main circuit, we use the integrated Four-Quarter Chopper to substitute the H bridge of the single-phase full-bridge VSI. The Four-Quadrant Chopper block represents a four-quadrant controlled chopper for converting a fixed DC input to a variable DC output. The block contains two bridge arms. Each bridge arm each has two switching devices.

Switching Devices		
Switching device	IGBT	
Forward voltage	0.8	V
On-state resistance	0.001	Ohm
Off-state conductance	1e-5	1/Ohm
Threshold voltage	6	V
Protection Diodes		
Model dynamics	Diode with no dynamics	
Forward voltage	0.8	V
On resistance	0.001	Ohm
Off conductance	1e-5	1/Ohm
Snubbers		
Snubber	None	

Figure 4: Parameters of Four-Quadrant Chopper

We use IGBT with anti-parallel diode as switching device here, detailed information can be found in Figure 4.

2.3 Pulse Generator

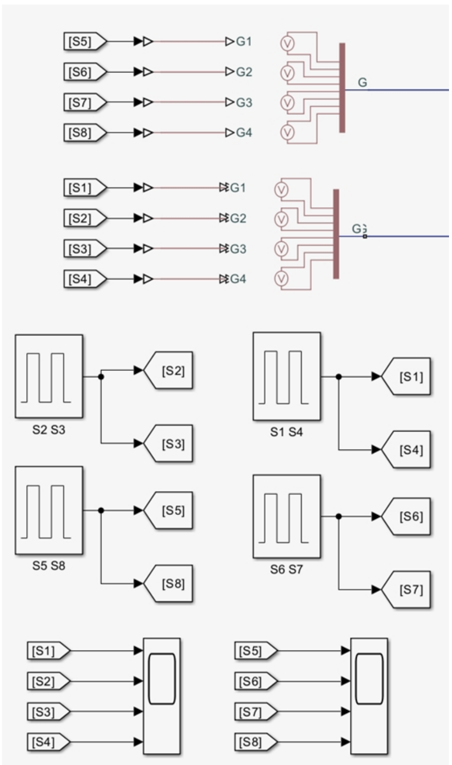


Figure 5: Gate Driver of IGBT

In this part we use four single pulse generators and two Four-Pulse Gate Multiplexers as IGBT gate driver. Taking account of 180° conducting mode, the pulse sequence of V1 and V4 is totally the same, which also applies to V2 and V3. Therefore, we only use four generators for two single VSIs in this topic.

Figure 6: V1, V4 (L) V2, V3 (R)

Figure 7: V5, V8 (L) V6, V7 (R)

With frequency being 50 Hz and 180° conducing mode, U_{G2} *and* U_{G3} is lagging U_{G1} *and* U_{G4} by 180 degrees, which means 0.01 sec. The value 'a' in Figure 7 refers to the external phase-shifting angle φ. By changing 'a' from 0° to 360° per degree, we will have smoother and more accurate curves of output voltage and other values.

3. Parameter Setup

R(Ω)	U_d(V)	θ(°)	φ(°)
8	400	180	1~360 per degree

3.1 Matlab program

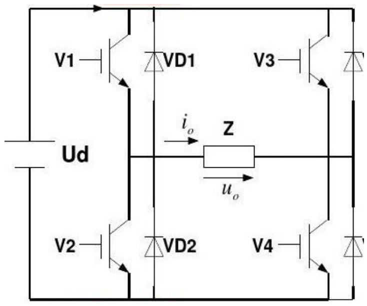
```
U1 = zeros(1,360);
U3 = zeros(1,360);
U5 = zeros(1,360);
U6 = zeros(1,360);
U7= zeros(1,360);
U9 = zeros(1,360);
THD= zeros(1,360);
phi=zeros(1,360);
i=1;
for a = 1:1:360
sim('part01.slx')
U1(i) = u1(2);
U3(i) = u3(2);
U5(i) = u5(2);
U6(i) = u6(2);
```

```
U7(i) = u7(2);
U9(i) = u9(2);
THD(i) = thd(2);
phi(i)=a;
i=i+1;
end
 figure(1);
     plot(phi,U1,'LineWidth',2)
     xlabel('external phase angle');
     ylabel('fundamental component (RMS) of output voltage','fontname','times new roma');
  axis([0,360,0,inf]);
   figure(2);
     plot(phi,U3,'LineWidth',2)
     xlabel('external phase angle');
     ylabel('3th harmonic voltage','fontname','times new roma');
       axis([0,360,0,inf]);
   figure(3);
     plot(phi,U5,'LineWidth',2)
     xlabel('external phase angle','LineWidth',2);
     ylabel('5th harmonic voltage','fontname','times new roma');
  axis([0,360,0,inf]);
       figure(4);
     plot(phi,U6,'LineWidth',2)
     xlabel('external phase angle','LineWidth',2);
     ylabel('6th harmonic voltage','fontname','times new roma');
  axis([0,360,0,inf]);
       figure(5);
     plot(phi,U7,'LineWidth',2)
     xlabel('external phase angle');
     ylabel('7th harmonic voltage','fontname','times new roma');
       axis([0,360,0,inf]);
       figure(6);
     plot(phi,U9,'LineWidth',2)
     xlabel('external phase angle');
     ylabel('9th harmonic voltage','fontname','times new roma');
       axis([0,360,0,inf]);
      figure(7);
     plot(phi,THD)
     xlabel('external phase angle');
     ylabel('THD');
       axis([0,360,0,inf]);
```

4. Simulation Results

4.1 Task one

In this task, we are required to observe the single invertor's time sequence waveform and input/output voltage relationships.



As the load in this part is purely resistive, we can only analyze the voltage waveform here.

When θ=180°:

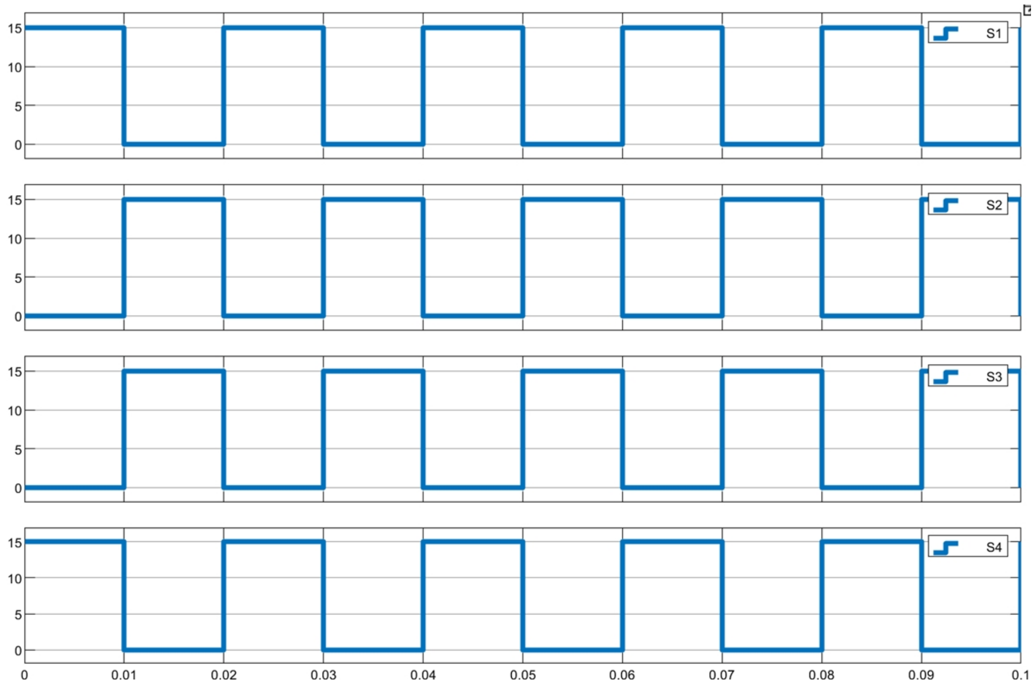


Figure 8: Gate Voltage Waveform from V1 to V4 ($\theta = 180°$)

	V1	V2	V3	V4
0°~180°	on	off	on	off
180°~360°	off	on	off	on

From the figure above, we can see that the gate voltage of V1 and V2 is complimentary, so does VT3 and VT4.

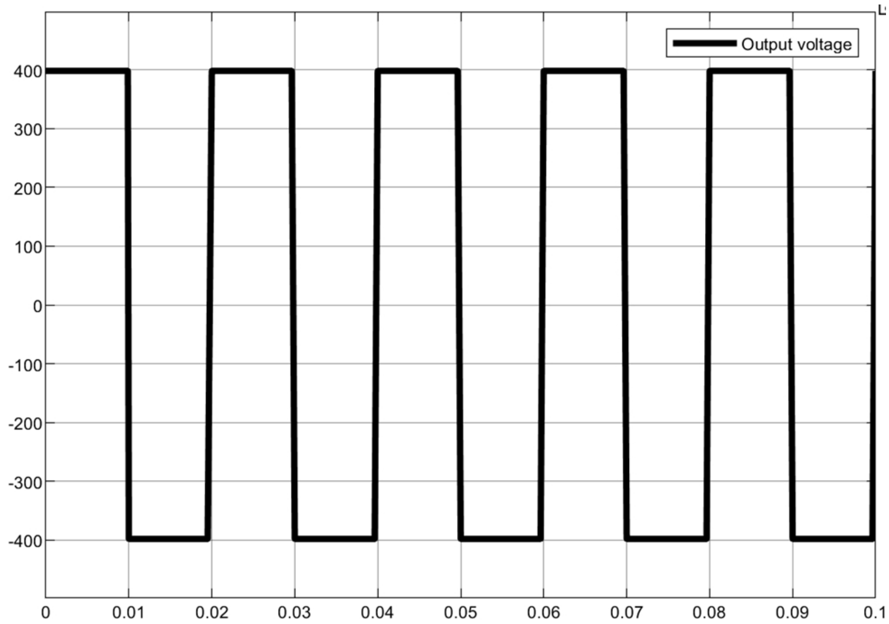


Figure 9: Waveform of output voltage ($\theta = 180°$)

Therefore, the output voltage is a square wave, with its amplitude being the same as voltage source which is 400V.

When θ=60°:

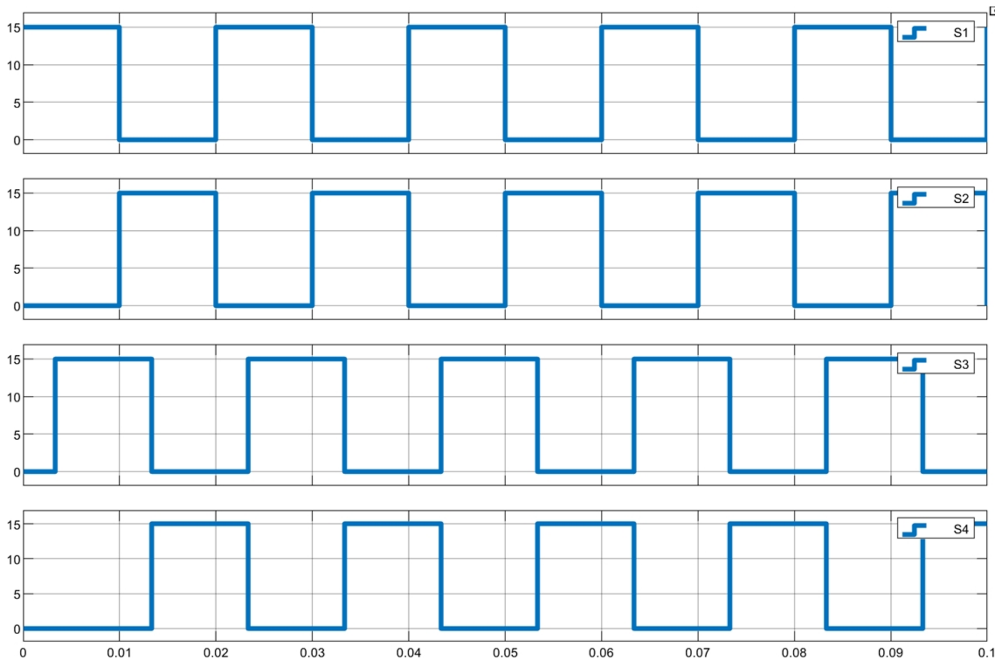


Figure 10: Waveform of output voltage ($\theta = 60°$)

From Figure 10, we can see that the phase angle of V3 is lagging 60° to V1, and V4 is lagging 60° to V2.

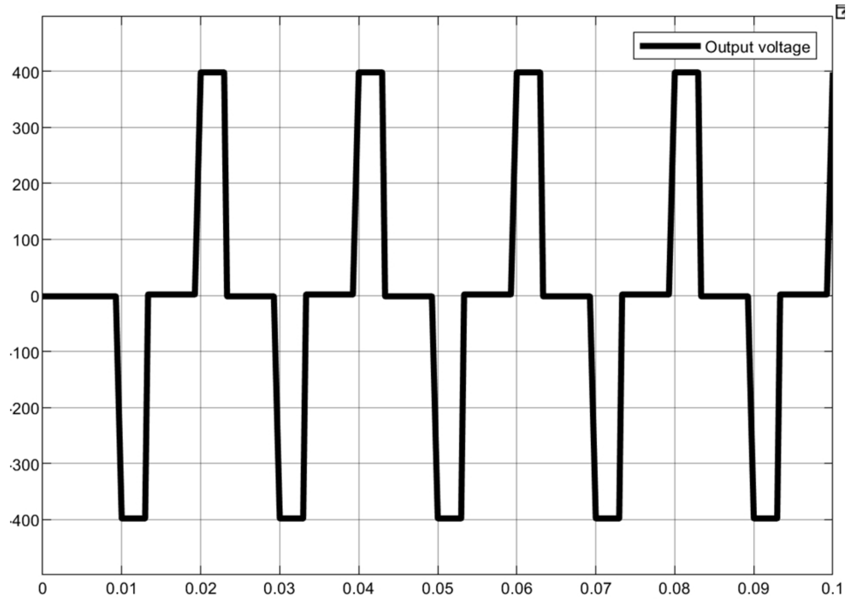


Figure 11: Gate Voltage Waveform from V1 to V4 ($\theta = 60°$)

From Figure 11, we can see that the output voltage waveform is a series of alternative polarity pulses with the pulse width being 60°.

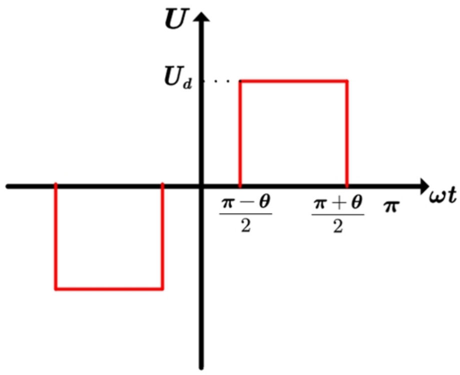


Figure 12: The relationship between output voltage and θ

To sum up, we can alternate the pulse width of output voltage by changing θ.

The Fourier series of output voltage can be calculated as:

$$u_1 = \sum_{n=1}^{\infty} \frac{4U_d}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\theta}{2} \sin(n\omega t)$$

Through this equation, we can see that there are no even harmonic components in the output voltage. When $\theta = 180°$, all odd harmonic components of output voltage avoid being eliminated.

4.2 Task two

In this task, we are required to **study the basic operating principle of series connection of multiple single-phase VSIs.** Series connection here means putting output in series.

During this process, we will always use the 180° conducting mode as required, which means u_1 *and* u_2 contain all the odd harmonic components.

From previous section, we can know that the Fourier series of voltage u_1 is:

$$u_1 = \sum_{n=1}^{\infty} \frac{4U_d}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\theta}{2} \sin(n\omega t)$$

Shift the conducting phase of two single-phase full-bridge invertors by φ, we can see:

$$u_2 = \sum_{n=1}^{\infty} \frac{4U_d}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\theta}{2} \sin(n(\omega t - \varphi))$$

Therefore, the output voltage u_o shall be:

$$u_o = u_1 + u_2 = \sum_{n=1}^{\infty} \frac{8U_d}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\theta}{2} \cos\frac{n\varphi}{2} \sin\frac{n(2\omega t - \varphi)}{2}$$

Through this equation, we can clearly see the relationship between external phase-shifting angle and output voltage. With an assigned φ, we can know that when $n\varphi = (2k+1)\pi$ $(k = 0, 1, 2...)$, the n^{th} (k=0,1,2,3…) harmonic component of output voltage will be eliminated. For instance, when $\varphi = 60°$, the 3rd harmonic components will be eliminated in the output voltage, and the waveform of u_o is a rectangular wave with 120° pulse width.

4.3 Task three

Plot the curves characterizing the relationship between φ and RMS value of the fundamental component in output voltage,3rd 5th 6th 7th and 9th harmonics components, THD of output voltage.

4.3.1 RMS value of fundamental component of output voltage

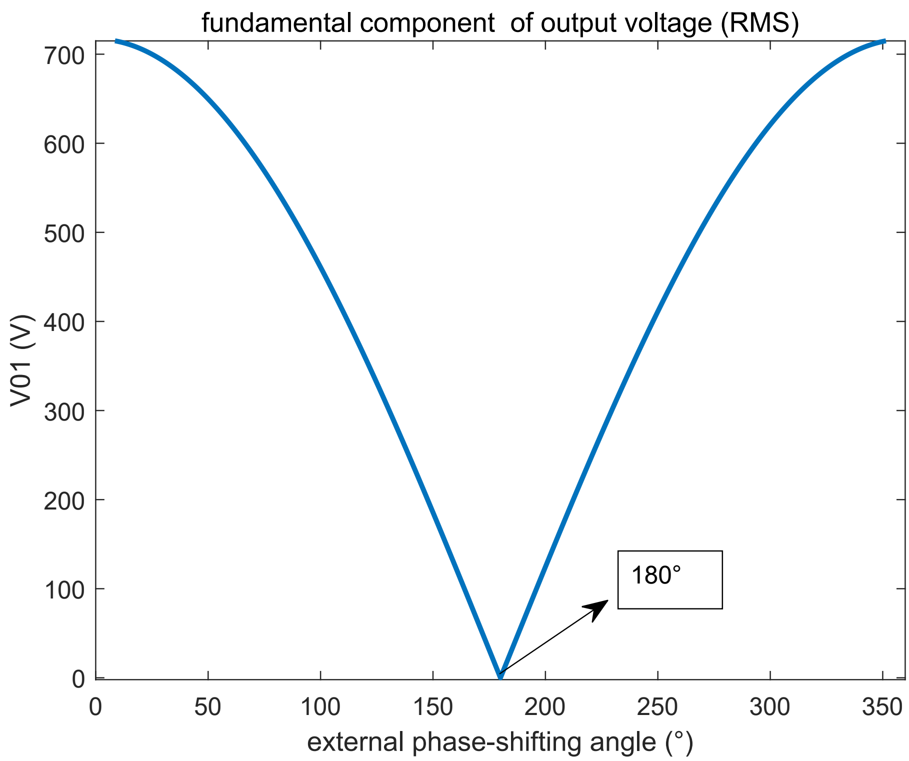


Figure 13: Plot between φ and fundamental component

Based on:

$$u_o = u_1 + u_2 = \sum_{n=1}^{\infty} \frac{8U_d}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\theta}{2} \cos\frac{n\varphi}{2} \sin\frac{n(2\omega t - \varphi)}{2}$$

When $\varphi=0°$ and $\theta = 180°$, the RMS value of fundamental component of output voltage can be calculated as:

$$U_{o1} = \frac{4\sqrt{2}U_d}{\pi} \approx 720\,(V)$$

In general, when n=1, and $\theta = 180°$, we can see:

$$U_{o1} = \frac{4\sqrt{2}U_d}{\pi} \cos\frac{\varphi}{2}$$

This equation can perfectly explain the waveform shown in Figure 13.

4.3.2 3rd 5th 6th 7th and 9th harmonics components

For all the harmonics component, we explore the relationship between amplitude of their voltage and external phase-shifting angle.

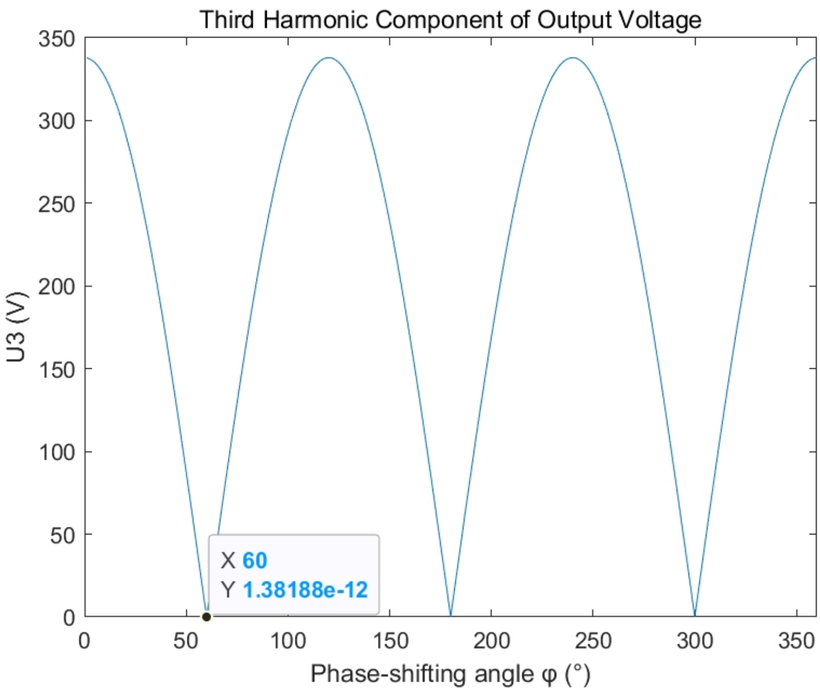


Figure 14: Plot between φ and 3rd harmonic component

Based on what has been mentioned above. We can see the amplitude of the waveform:

$$U_{o3m} = \frac{8U_d}{3\pi} \cos\frac{3\varphi}{2}$$

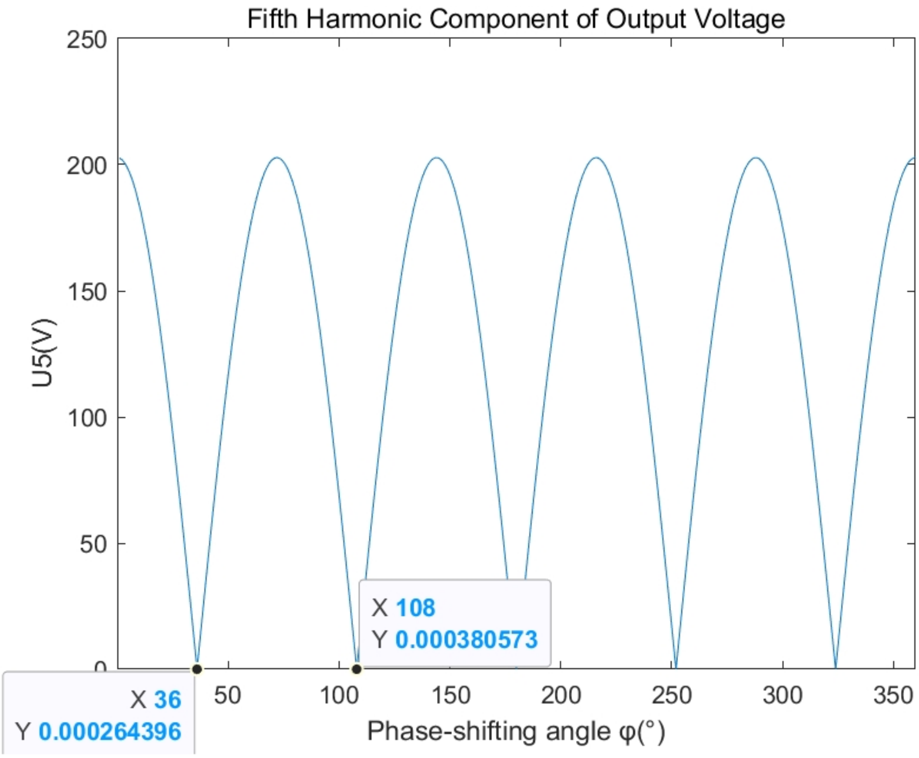


Figure 15: Plot between φ and 5th harmonic component

$$U_{o5m} = \frac{8U_d}{5\pi}\cos\frac{5\varphi}{2}$$

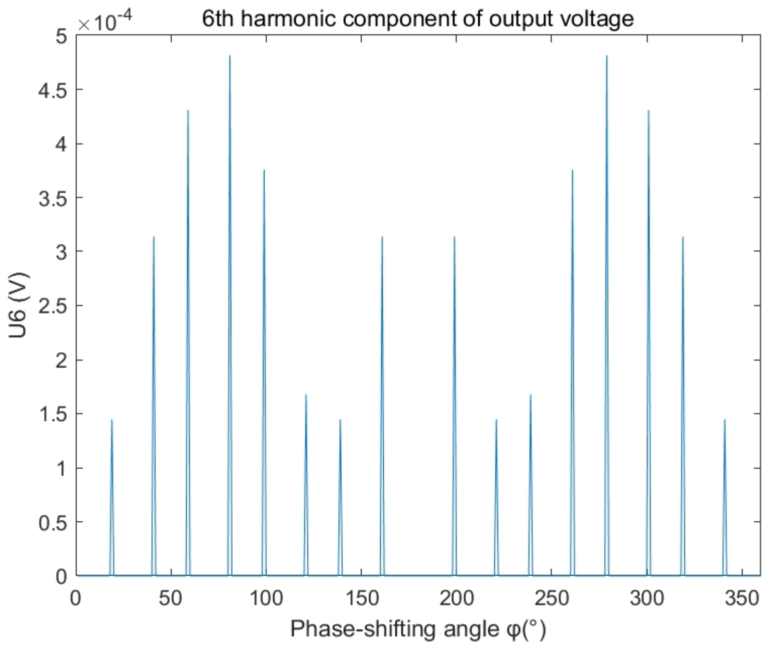


Figure 16: Plot between φ and 6th harmonic component

From

$$u_o = u_1 + u_2 = \sum_{n=1}^{\infty}\frac{8U_d}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\theta}{2}\cos\frac{n\varphi}{2}\sin\frac{n(2\omega t-\varphi)}{2}$$

We can see that there is nearly no even harmonics component.

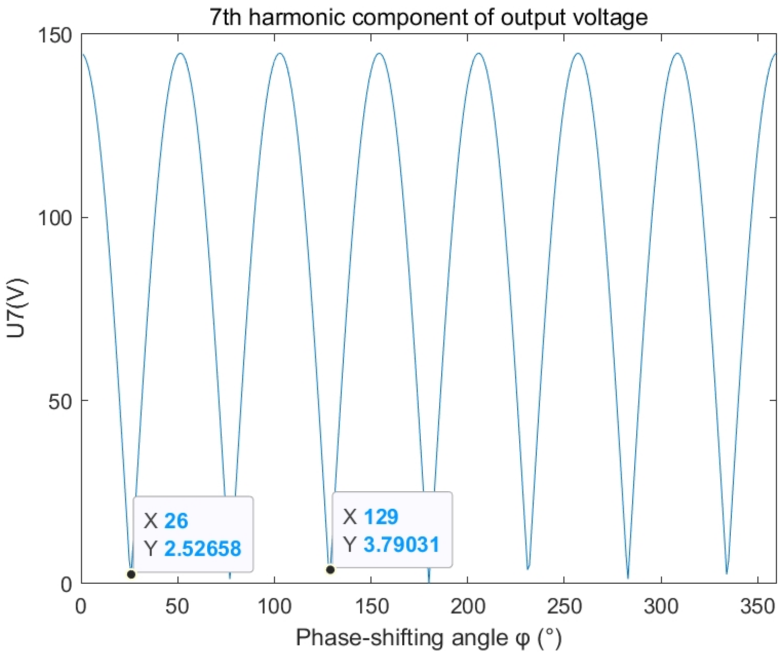


Figure 17: Plot between φ and 7th harmonic component

$$U_{o7m} = \frac{8U_d}{7\pi}\cos\frac{7\varphi}{2}$$

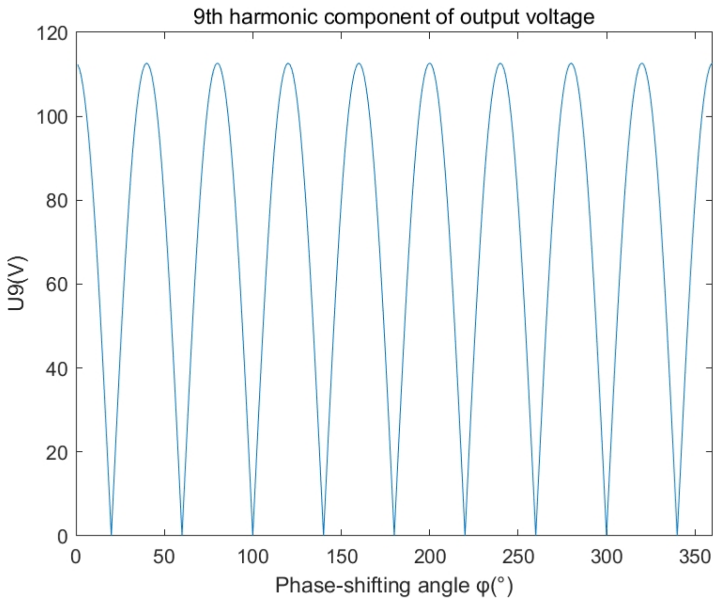


Figure 18: Plot between φ and 8th harmonic component

$$U_{o9m} = \frac{8U_d}{9\pi}\cos\frac{9\varphi}{2}$$

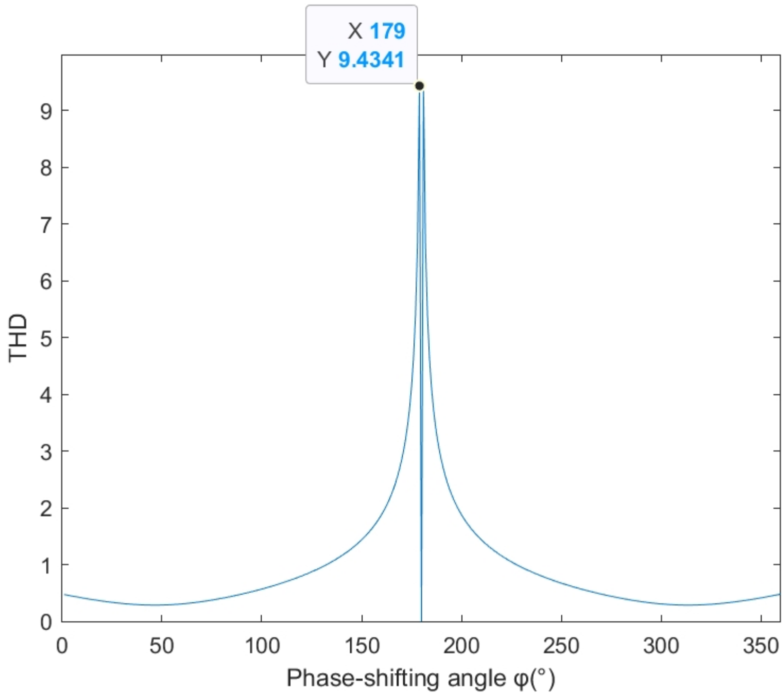


Figure 19: Plot between φ and THD of Output Voltage

We can analyze THD from a qualitative perspective: When φ varies from 0° to 60°, the third harmonic component will decrease to zero, which is the largest of all the harmonic components. Thus, total THD will slightly decrease since the fundamental component also reduces. But as fundamental component goes on decreasing, the harmonic components will rise up to infinity, where φ is infinitely close to 180°. When φ=180°, output voltage is zero. However, φ is a discrete value whose step size is 1°. Therefore, the plot of MATLAB has accidentally matched the line from value of 179°with axis at 180°.

Topic 2

1. Topic

For topic 2, we need to analyze the three-phase bridge invertor. To be more specific, we need to analyze the voltage across the power switch and the current flowing through it. Besides, we need to compare the simulation results of 5th 7th 11th and 13th harmonics components in output voltage and output current with theoretical ones.

2. Simulation Model

2.1 Three-phase VSI

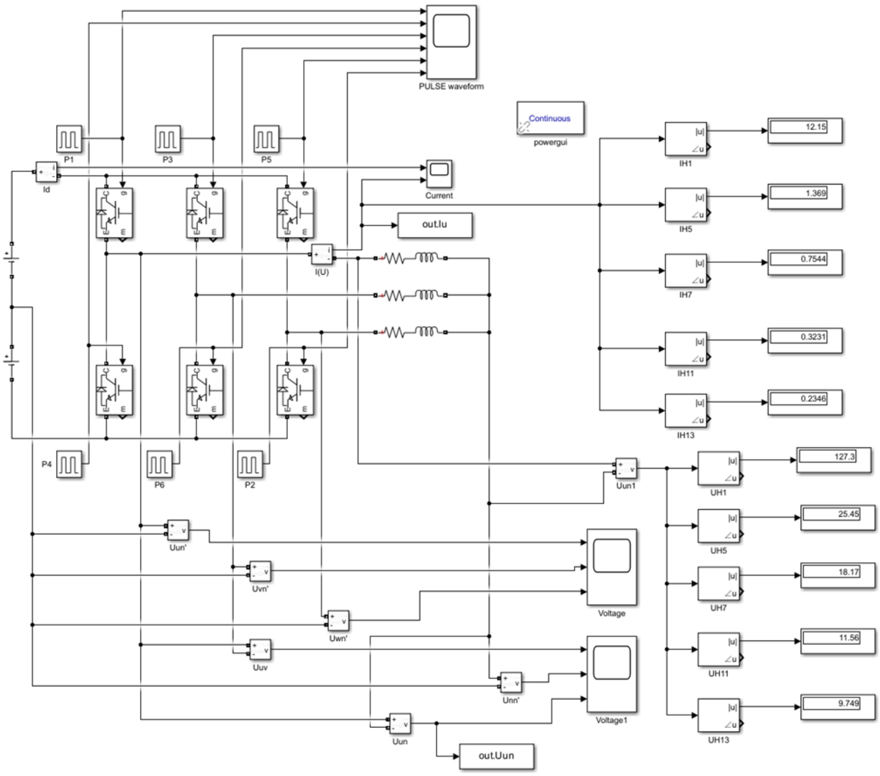
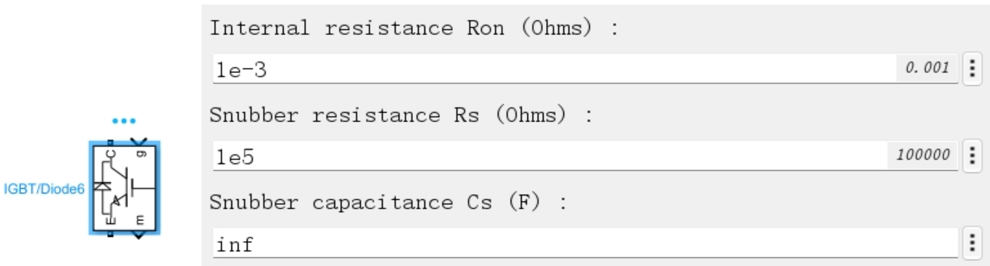


Figure 20: Simulation Model of topic 2

Unlike Topic 1, we do not use any integrated block in this model, mainly because it is important to comprehend the arrangement order of each IGBT switch and easier to measure the phase and line voltage. This model is pretty simple, which consists of 2 DC voltage sources, one three-phase bridge with six arms, one three-phase RL load and six pulse generators.



Here is the parameter of IGBT switching device we used.

2.2 Conducting Sequence

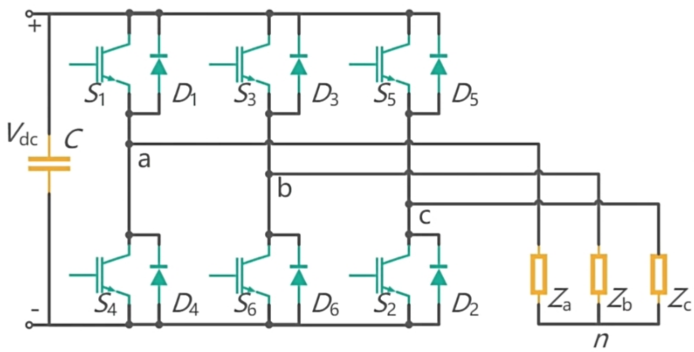


Figure 21: Three-phase Inverter

To begin with, we need to know the conducting sequence of each device. As what has been shown *in Figure 21, conducting sequence is from 1 to 6. It is noticed that lower arms does not have the same arrangement order as the upper ones. Usually we adopt 180° conducting mode, which means duty cycle of each gate pulse signal is set to be 50%.*

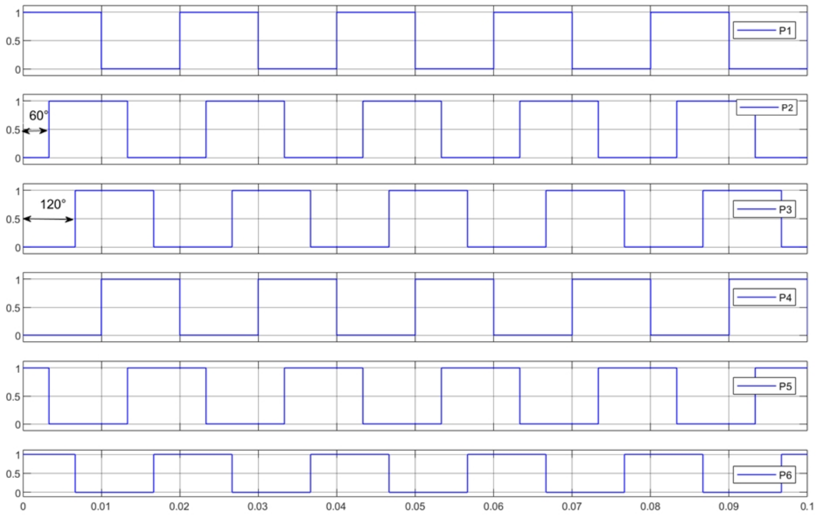


Figure 22: Waveform of pulse signals

Figure 22 shows the sequence of driving signals of 6 IGBT switching devices. We can see that there are three rules:

1) Six IGBT devices are triggered in sequence from 1 to 6 and there is a phase difference of 60 degrees between every adjacent(refers to conducting sequence, not actual position) two signals.
2) Two bridge arms of the same phase conduct electricity alternately, and the angle at which each phase begins to conduct electricity differs by 120 degrees.
3) Each commutation occurs between the upper and lower bridge arms of the same phase, hence we refer to it as longitudinal commutation

3. Parameter Setup

R(Ω)	U_d(V)	L(mH)	f(Hz)
10	200	10	50

4. Simulation Results

4.1 Voltage across power switch and the current flowing through it

From the following figure, we can view the voltage and current waveform of each switching device.

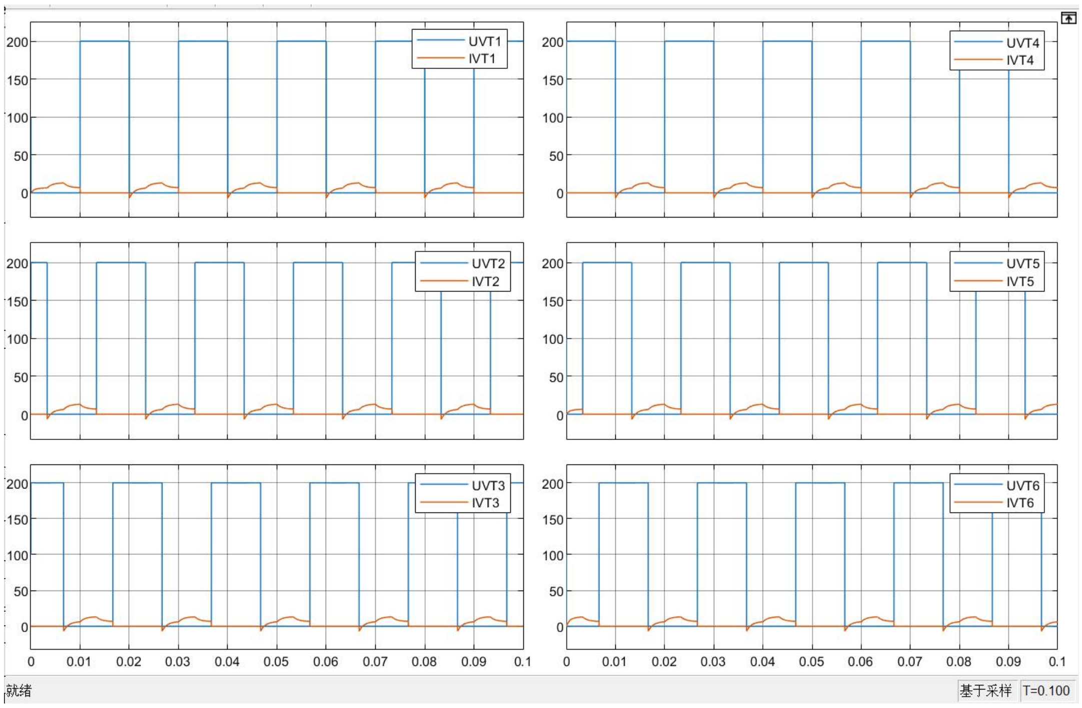


Figure23: current signal and voltage signal for each switching device

4.1.1 Voltage across power switch

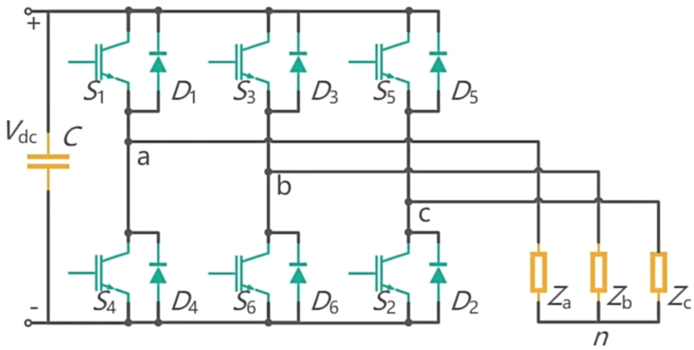


Figure24: Three-phase inverter

For phase a (a,b,c in Figure 24 separately corresponds to u,v,w):

When arm 1 is conducting:

$$u_{UN'} = \frac{U_d}{2}$$

While when arm 4 is conducting:

$$u_{UN'} = -\frac{U_d}{2}$$

Since the whole circuit works under 180° conducting mode, we can know that $u_{UN'}$ is a square wave. The same applies to other phases.

The load-side line voltage: u_{UV} u_{VW} u_{WU} can be obtained from these equations

$$\begin{cases} u_{UV} = u_{UN'} - u_{VN'} \\ u_{VW} = u_{VN'} - u_{WN'} \\ u_{WU} = u_{WN'} - u_{UN'} \end{cases}$$

N’ refers to the imaginary midpoint of the DC power supply. We can further get the load-side phase voltage:

$$\begin{cases} u_{UN} = u_{UN'} - u_{NN'} \\ u_{VN} = u_{VN'} - u_{NN'} \\ u_{WN} = u_{WN'} - u_{NN'} \end{cases}$$

Then our work is to calculate the $u_{NN'}$. Through some simple processes, we can see:

$$u_{NN'} = \frac{u_{UN'} + u_{VN'} + u_{WN'}}{3} - \frac{u_{UN} + u_{VN} + u_{WN}}{3} = \frac{u_{UN'} + u_{VN'} + u_{WN'}}{3}$$

Where $u_{UN} + u_{VN} + u_{WN}$ =0 because of a symmetrical three-phase load.

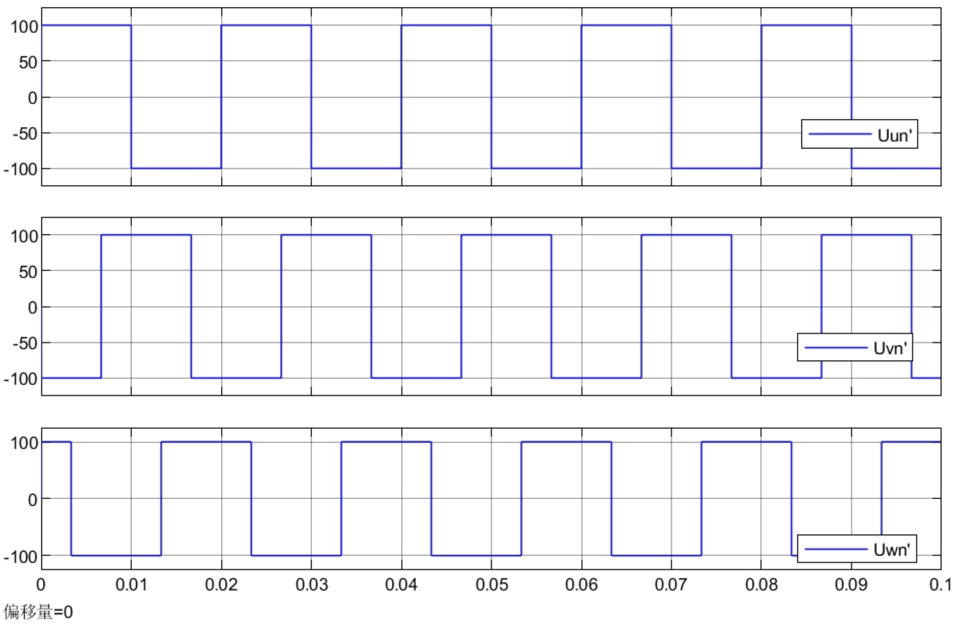


Figure 25: U, V, W phase and DC neutral voltage waveforms

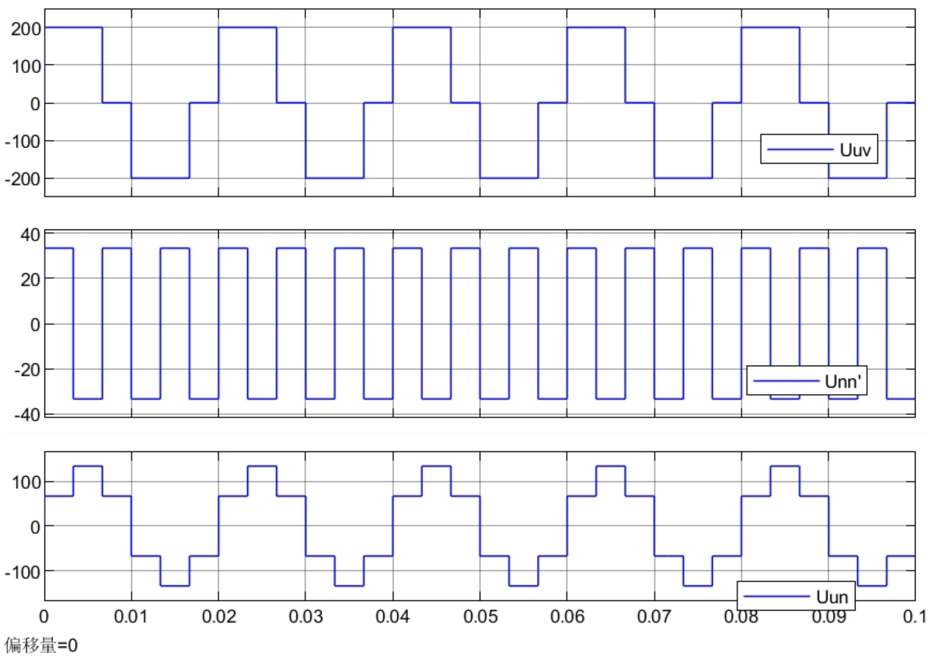


Figure 26: u_{UV}, $u_{NN'}$, u_{UN} waveforms

4.1.2 Current flowing through the switch

Since this is a three-phase VSI, we can know that the waveform of current is determined by the impedance angle φ.

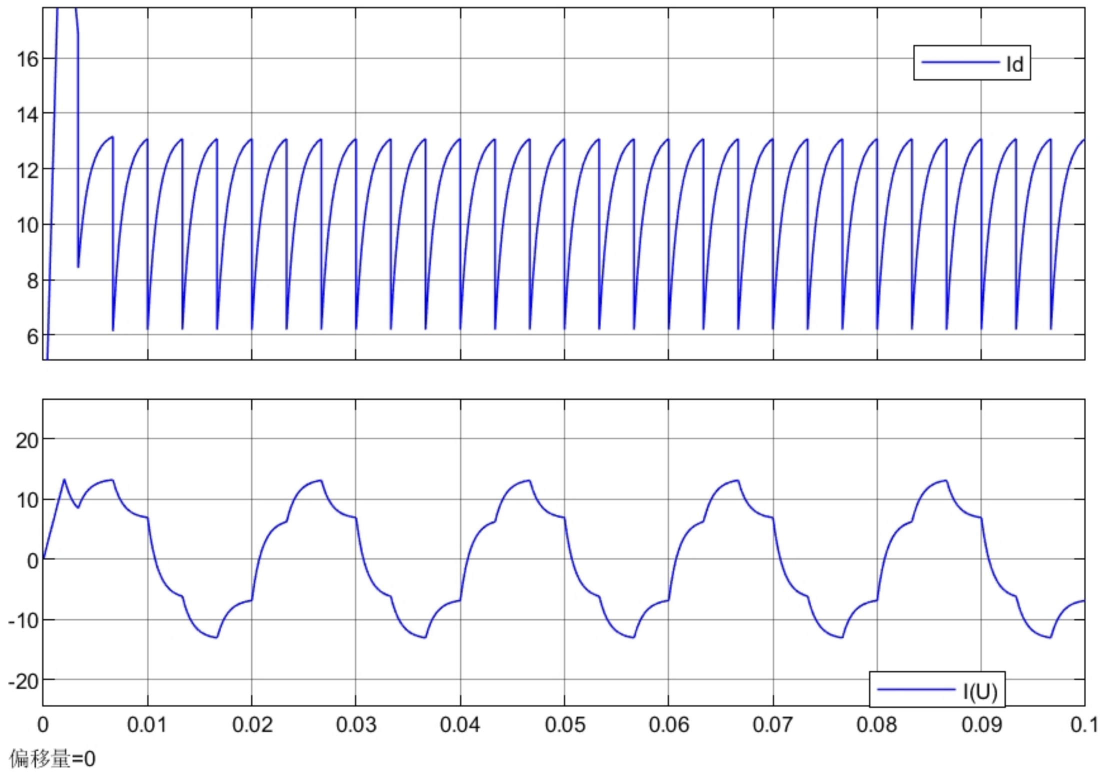


Figure 27: the waveforms of DC current id and phase U current iu

The impedance angle for our group is smaller than 60 degree. The waveform of i_u is similar to i_V i_W except from 120° phase difference. DC side current i_d could be obtained by adding current of arm 1,3,5 together. From Figure 27, we can see Id has an impulse every 60°, while DC voltage almost remains stable. Thus, the power transmitted from AC side to DC is determined by current.

4.2 Calculation and analysis of fundamental component and harmonic components

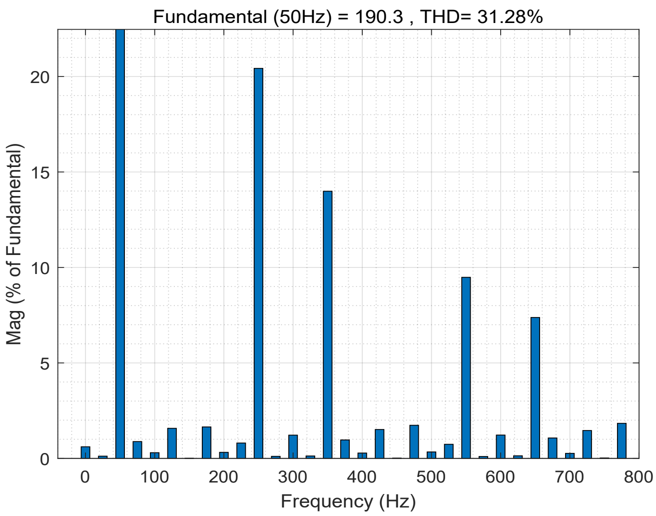


Figure 28: voltage harmonic analysis

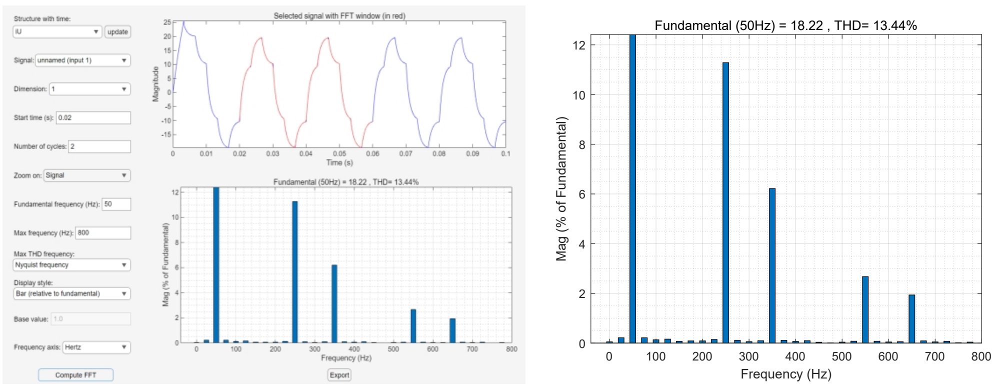


Figure 29: current harmonic analysis

Through FFT Analysis tool of Powergui module in simulink, the fifth, seventh, eleventh and thirteenth harmonics of load phase voltage and current are separately calculated and compared with the theoretical values.

From Fourier series, we can know the load phase voltage

$$u_{UN} = \frac{2U_d}{\pi}\left(\sin\omega t + \sum_n \frac{1}{n}\sin n\omega t\right), n = 6k \pm 1$$

$$U_{UN1m} = \frac{2U_d}{\pi}$$

the kth harmonics component in output voltage

$$U_{UNkm} = \frac{U_{UN1m}}{k}$$

The comparison between simulation voltage values and theoretical ones is listed below:

	Theoretical Value	Simulation Value	Error(%)
RMS value of fundamental wave/V	127.28	127.3	0.02%
the 5th harmonic /%	20	19.99	0.05%
the 7th harmonic /%	14.28	14.27	0.07%
the 11th harmonic /%	9.09	9.08	0.11%
the 13th harmonic /%	7.69	7.66	0.39%

Current can be determined to divide voltage by impedance.

$$i_U = \frac{u_{UN}}{\sqrt{(\omega L)^2 + R^2}}$$

$$I_{UN1} = \frac{U_{UN1}}{\sqrt{(\omega L)^2 + R^2}} = \frac{90}{\sqrt{(\pi)^2 + 10^2}} = 12.1427A$$

the 5th harmonics component in output current

$$I_{UN5} = \frac{U_{UN5}}{\sqrt{(5\omega L)^2 + R^2}} = \frac{\frac{90}{5}}{\sqrt{(5\pi)^2 + 10^2}} = 1.3671A$$

$$\frac{I_{UN5}}{I_{UN1}} = 11.26\%$$

the 7th harmonics component in output current

$$I_{UN7} = \frac{U_{UN7}}{\sqrt{(7\omega L)^2 + R^2}} = \frac{\frac{90}{7}}{\sqrt{(7\pi)^2 + 10^2}} = 0.7526A$$

$$\frac{I_{UN7}}{I_{UN1}} = 6.20\%$$

the 11th harmonics component in output current

$$I_{UN11} = \frac{U_{UN11}}{\sqrt{(11\omega L)^2 + R^2}} = \frac{\frac{90}{11}}{\sqrt{(11\pi)^2 + 10^2}} = 0.3216A$$

$$\frac{I_{UN11}}{I_{UN1}} = 2.65\%$$

the 13th harmonics component in output current

$$I_{UN13} = \frac{U_{UN13}}{\sqrt{(13\omega L)^2 + R^2}} = \frac{\frac{90}{13}}{\sqrt{(13\pi)^2 + 10^2}} = 0.2329A$$

$$\frac{I_{UN13}}{I_{UN1}} = 1.92\%$$

The comparison between simulation current values and theoretical ones is listed below:

	Theoretical Value	Simulation Value	Error(%)
RMS value of fundamental wave/A	12.1427	12.15	0.60%
the 5th harmonic /%	11.26	11.27	0.09%
the 7th harmonic /%	6.20	6.21	0.16%
the 11th harmonic /%	2.65	2.66	0.38%
the 13th harmonic /%	1.92	1.93	0.52%