Seminar 4

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Topic 1

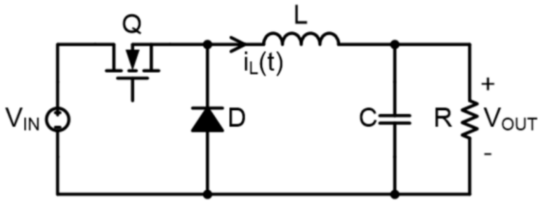
1. Topic

For topic 1, we need to analyze the buck converter and its major parameters. To be more specific, we need to carry out two tasks:

1) Calculate the theoretical values of inductor current ripple and capacitor voltage ripple with given circuit parameters, then compare them with simulation results.
2) Find the relationships between Duty Cycle and inductor current ripple, capacitor voltage ripple, and voltage gain with duty cycle D varying from 0 to 0.8.

2. Simulation Model

2.1 Simulation Schematic



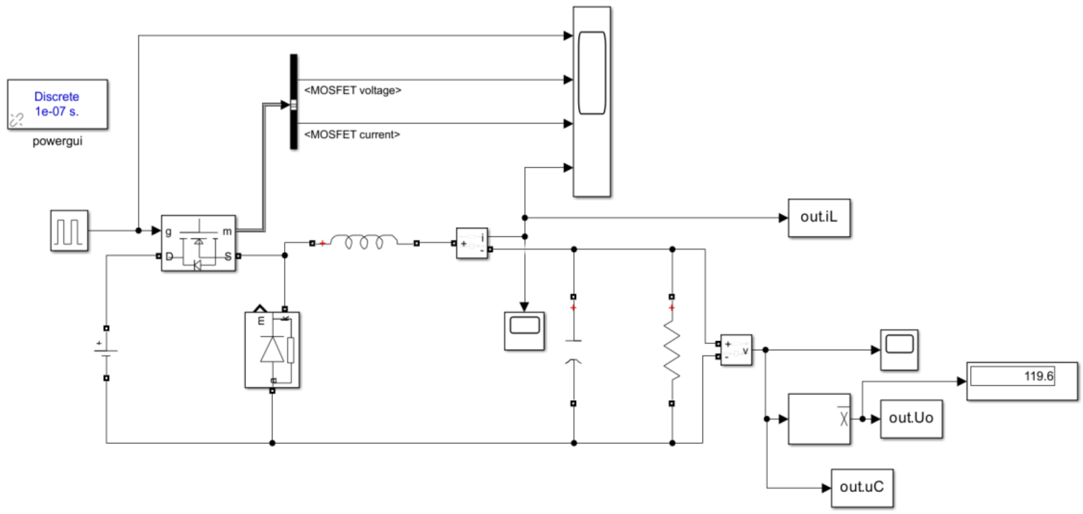
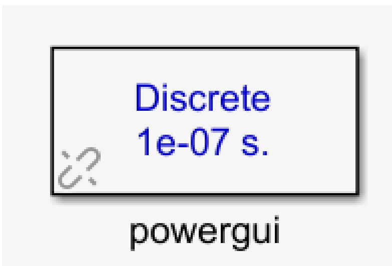


Figure 1: Simulation Circuit of Buck converter



In this topic, we set the sampling time as 0.1 μs and stopping time as 0.15s. Since fs is 100kHz, we can measure 100 points within one period. The current flowing through the inductor, voltage across capacitor and output voltage are separately displayed on the working zone of MATLAB so that we can calculate the ripple components and voltage gain when duty cycle is variable. We choose data after 0.1s to analyze so that we can avoid the starting transient state of the Buck circuit.

3. Parameter Setup

3.1 Major Parameter

Converter Type	Vin	Vo	RL	fs	L	C
Buck	200V	120V	60ohm	100kHz	4mH	50μF

Based on the given parameters and theory from Buck converter, we can calculate the duty cycle of the pulse generator:

$$D=\frac{U_o}{U_i}=0.6$$

3.2 Device Parameter

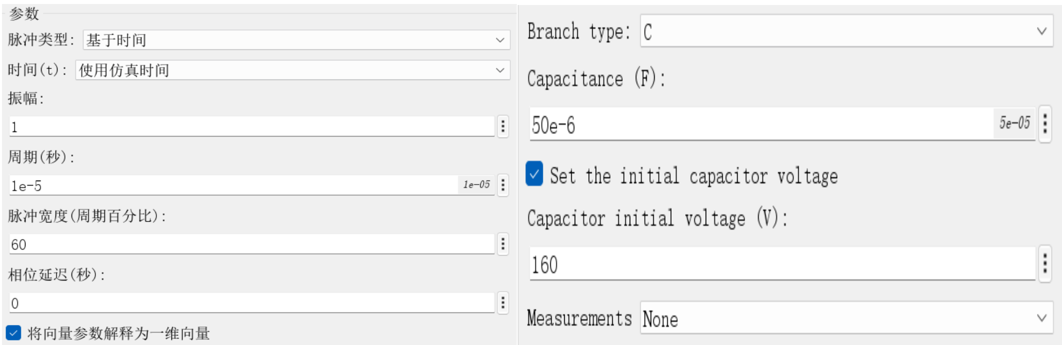


Figure 2: Parameters of Pulse Generator (L) and Capacitor (R)

We set capacitor initial voltage as 160V so that the Buck circuit can reach the steady state faster.

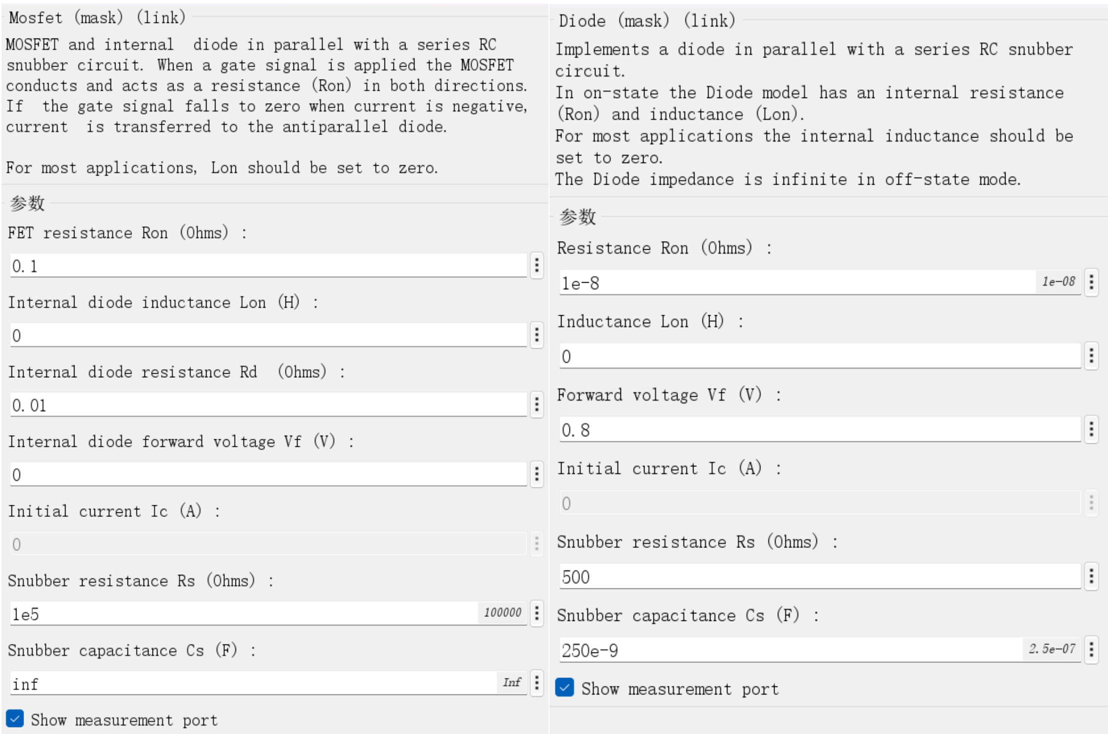


Figure 3: Parameters of Mosfet (L) and Diode (R)

4. Simulation Results

4.1 Task one

Calculate the theoretical values of inductor current ripple and capacitor voltage ripple with given circuit parameters, then compare them with simulation results.

4.1.1 Theoretical Calculation

To indicate the ripple component, we need to calculate the difference between the maximum and minimum values of the inductor current and capacitor voltage.

1) For inductor current:

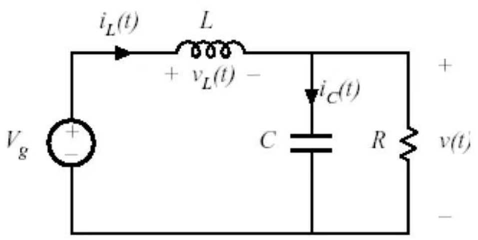


Figure 4: Subinterval of Buck when the switch is on

When the switch is on:

$$U_L = V_g - U_o$$

Then we can determine the slope of the inductor current:

$$\frac{di_L}{dt} = \frac{V_g - U_o}{L} = \frac{(1-D)U_i}{L}$$

Thus, we can calculate the ripple current of the inductor:

$$\varDelta I_L = \frac{(1-D)U_i}{L} t_{on} = \frac{D(1-D)U_i}{f_s L} = 120mA$$

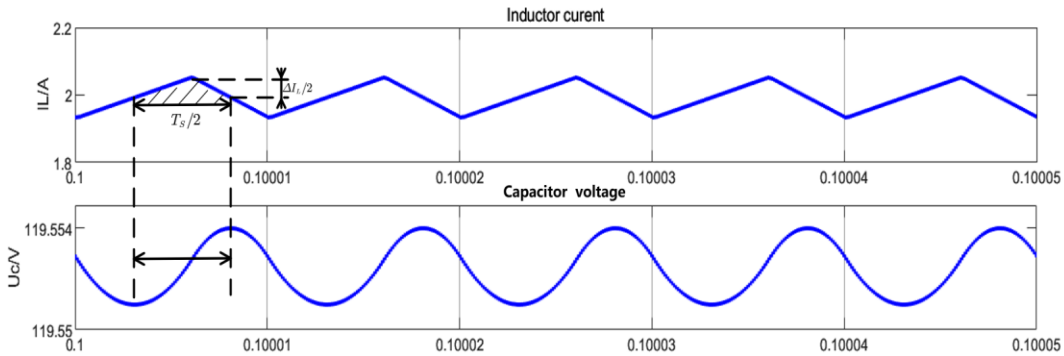


Figure 5: Waveform of inductor current and capacitor voltage

2) For capacitor voltage:

We know that:

$$I_C = I_R + I_L$$
$$I_R = I_o = U_o / R$$

Where I_R is a DC component. Thus,

$$\varDelta I_C = \varDelta I_L \,.$$

We can also explain this through superposition theory. Because load current is a DC component, the load can be regarded as an open circuit when analyzing ripple components (AC components).
Through the characteristics of capacitor, we can know:

$$\Delta u_C = \frac{1}{C}\int_{\frac{T_s}{2}} i_C\, dt = \frac{Q}{C}$$

Where Q refers to the shaded triangle area in Figure 4:

$$\Delta u_C = \frac{Q}{C} = \frac{1}{2C}\frac{T_S}{2}\frac{\Delta I_C}{2} = \frac{T_S \Delta I_L}{8C} = \frac{D(1-D)U_i}{8CLf_s^2} = 3mV$$

By the way, as the load resistor is rather small (60ohm) in our group, the circuit can always work under CCM mode whatever the duty cycle D is.

4.1.2 Simulation Result

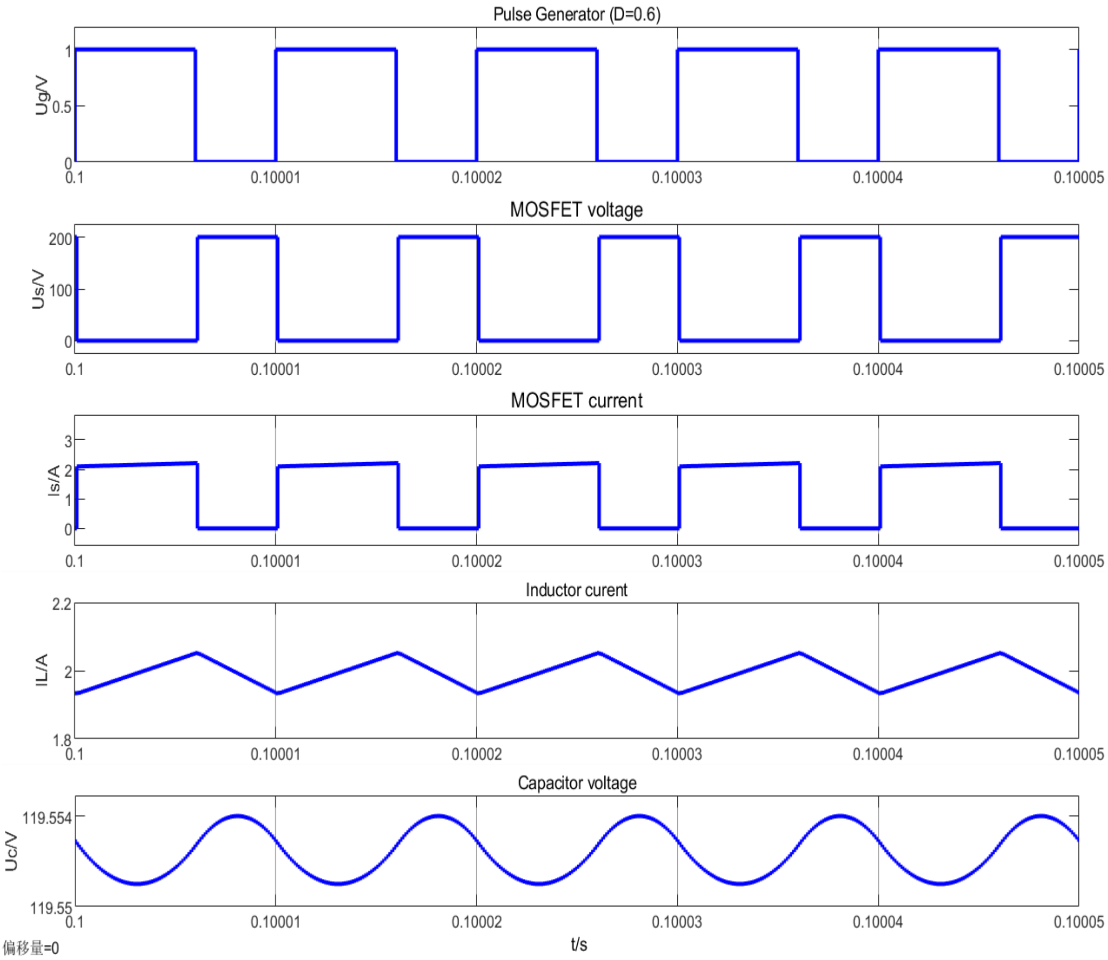


Figure 6: Waveform of the circuit

Based on the simulation model we established, we can measure the ripple component with Scope.

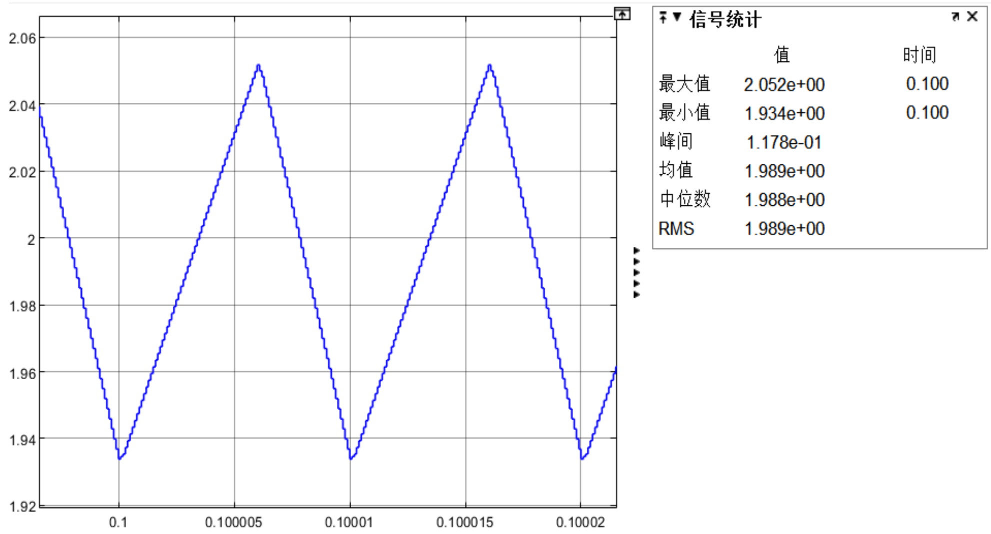


Figure 7: Measurement of ripple current

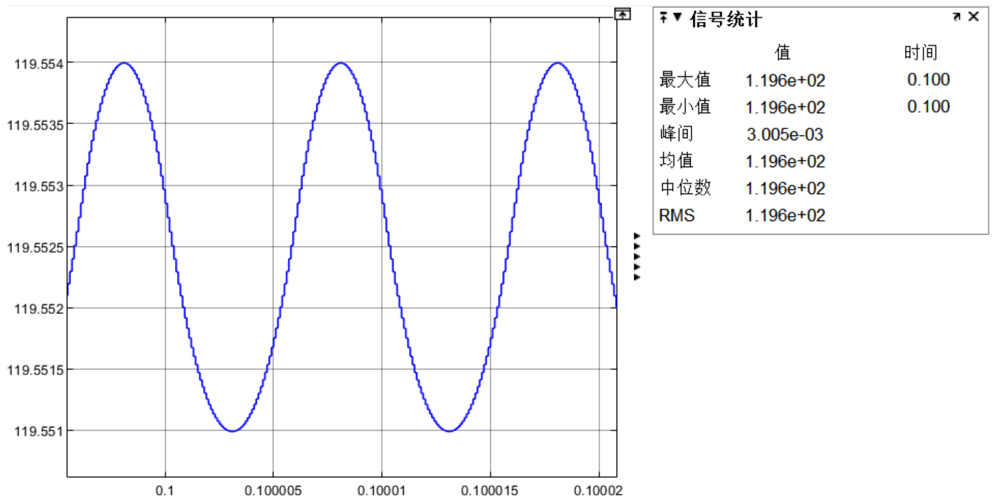


Figure 8: Measurement of ripple voltage

4.1.3 Comparison between Simulation Results and Theoretical Results

	Simulation	Theoretical Calculation	Error (%)
ΔI	117.8mA	120mA	1.84
ΔU	3.005mV	3mV	0.17

From the table above, we can see that the simulation result is quite identical with theoretical result and the error can be tolerated.

4.2 Task two

Describe the relationships between Duty Cycle and inductor current ripple, capacitor voltage ripple, and voltage gain with duty cycle D varying from 0 to 0.8.

4.2.1 MATLAB Program

Considering that duty cycle D is variable in task 2, we wrote the MATLAB program below to calculate the ripple value and generate the plots we want.

```
clc;clear;
N=81;k=1;
Uin=200;
dI=zeros(1,N); %电感电流纹波仿真值
dU=zeros(1,N); %电容电压纹波仿真值
Uout=zeros(1,N); %输出电压仿真值
G=zeros(1,N); % 电压增益仿真值
% 取 100 组数据来计算峰峰值，得出纹波
iL_period=zeros(1,100);uC_period=zeros(1,100);
tic %计时模块
for D=0.01:1:80.01
    out=sim('m1',[0,0.11]);
    for i=1:100
        iL_period(i)=out.iL.Data(1000000+i,1);
        uC_period(i)=out.uC.Data(1000000+i,1);
    end
    dI(k)=(max(iL_period)-min(iL_period));
    dU(k)=(max(uC_period)-min(uC_period));
    Uout(k)=out.Uo.Data(end);
    G(k)=Uout(k)/Uin;
    fprintf('循环第%d 轮\n',k);
    k=k+1;
end
toc
N=81;
g=1;
d2=0.0001;
dIcal=zeros(1,N); %电感电流纹波理论值
dUcal=zeros(1,N); %电容电压纹波理论值
Gcal=zeros(1,N); % 电压增益
for d1=0.01:1:80.01
    dIcal(g)=200*d2*(1-d2)/400;
    dUcal(g)=200*d2*(1-d2)/16000;
    Gcal(g)=d2;
    g=g+1;
    d2=d2+0.01;
end
%% 数据制图
d=0.01:1:80.01;
figure(1)
dI=1000*dI; %单位为 mA
dIcal=1000*dIcal;
plot(d,dI,'b-');
hold on;
```

```
plot(d,dIcal,'r-');
legend('Simulation results','Theoretical results')
xlabel('$D/\%$','Interpreter','latex');
ylabel('$\Delta I/ \mathrm{mA}$','Interpreter','latex');
title('$\Delta I=f(D)$','Interpreter','latex');

figure(2)
dU=1000*dU; %单位为 mV
dUcal=1000*dUcal;
plot(d,dU,'b-');
hold on;
plot(d,dUcal,'r-');
legend('Simulation results','Theoretical results')
xlabel('$D/\%$','Interpreter','latex');
ylabel('$\Delta U/ \mathrm{mV}$','Interpreter','latex');
title('$\Delta U=f(D)$','Interpreter','latex');

figure(3)
plot(d,G,'b-');
hold on;
plot(d,Gcal,'r-');
legend('Simulation results','Theoretical results')
xlabel('$D/\%$','Interpreter','latex');
ylabel('$G$','Interpreter','latex');
title('$G=f(D)$','Interpreter','latex');
```

4.2.2 Simulation Result

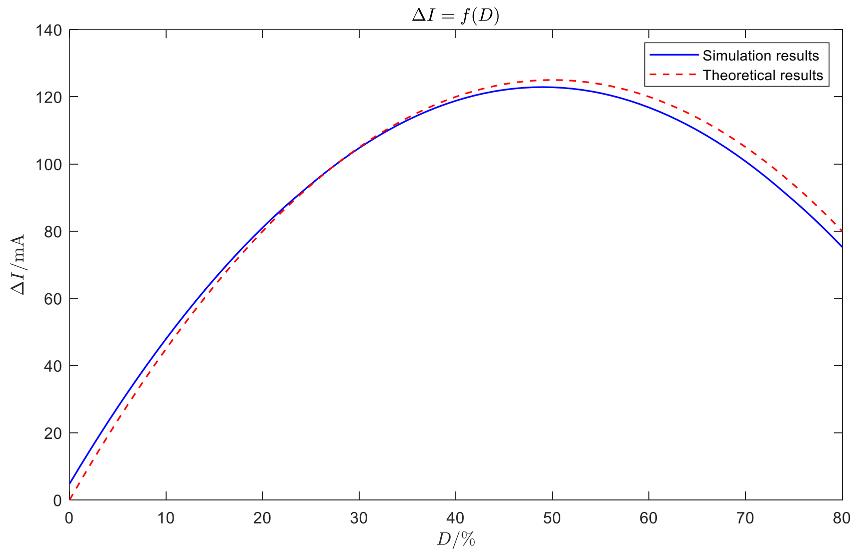


Figure 9: Relationship between D and inductor ripple current

$$\Delta I_L = \frac{D(1-D)U_i}{f_s L}$$

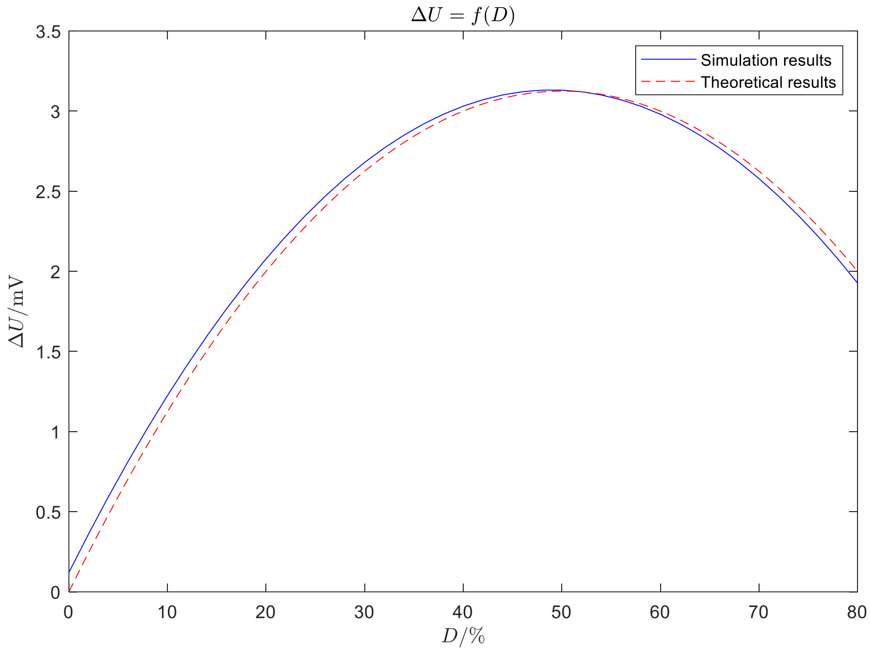


Figure 10: Relationship between D and capacitor ripple voltage

$$\Delta u_C = \frac{D(1-D)U_i}{8CLf_s^2}$$

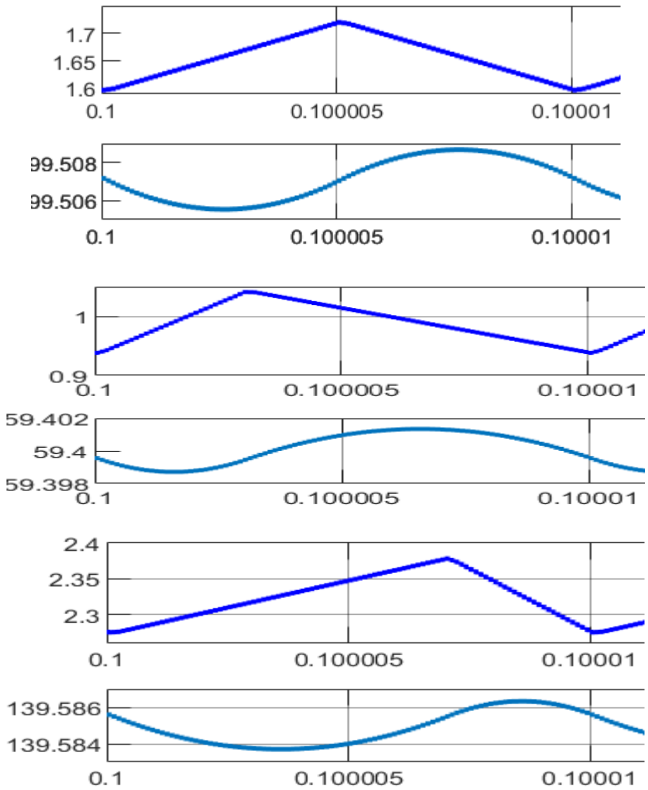


Figure 11: Inductor current ripple and capacitor voltage ripple (D=0.5, 0.3 0.7)

From plots and theoretical equations, we can see that the ripple component is symmetrical about point when D=0.5.

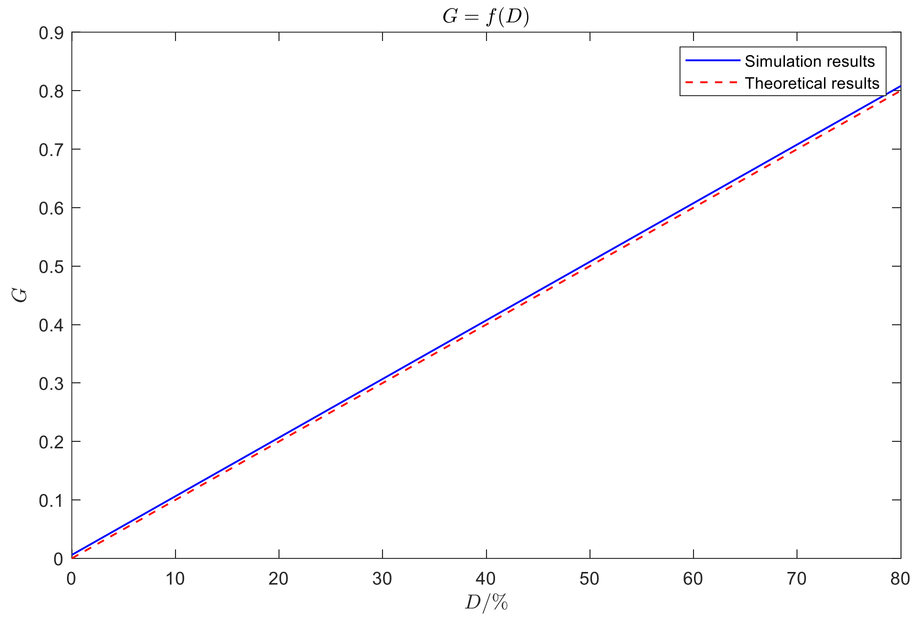


Figure 12: Relationship between D and voltage gain

$$\frac{U_o}{U_i} = D$$

From figure 12, we can see there is still rather small difference between two results. Typically, output voltage is always considered as DC component in theory, while there is still little ripple component shown in Figure 13. Besides, the on-state resistance of switch is always neglected in theory. So it makes sense for the error generated here.

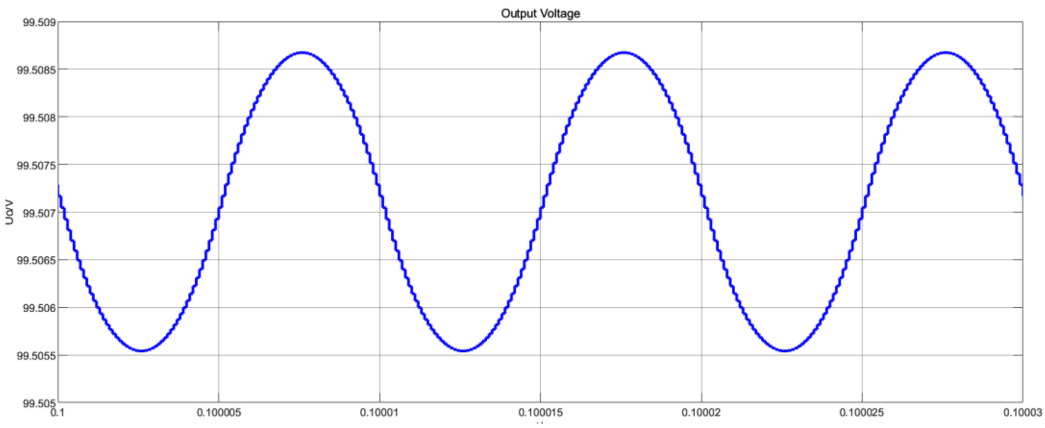


Figure 13: Output voltage ripple

Based on what has been mentioned above, we can see the simulation curves fit really well with the theoretical ones and the error is acceptable.

Topic 2

1. Topic

For topic 2, we need to study the Isolated DC to DC chopper, which is composed of a full-bridge inverter and full-wave rectifier. There are three tasks to be carried out.

1) For given input/output voltage and circuit parameters, do simulations to study the operating principle and analyze the operating sequence.
2) Adjust the load resistor to realize ***continuous current mode*** (**CCM**) and ***discontinuous current mode*** (**DCM**) and verify through simulation.
3) Adjust duty cycle ***D*** and analyze the relationships between ***D*** and ***voltage gain (G=Vo/Vin)***

2. Simulation Model

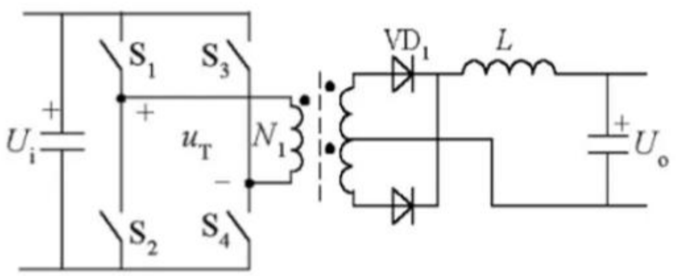


Figure 14: Circuit Diagram

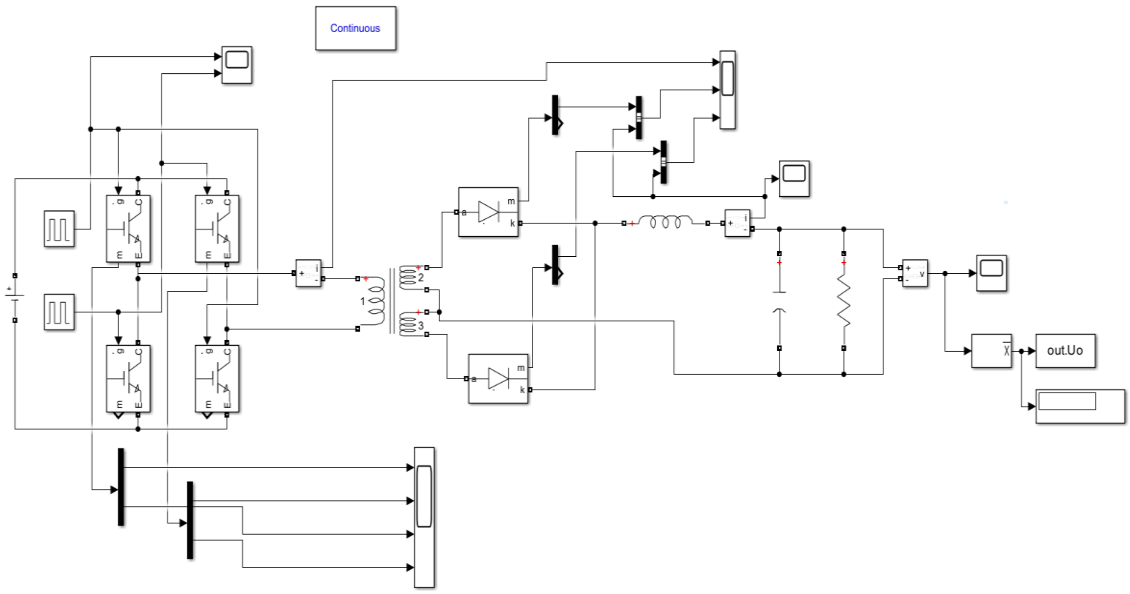


Figure 15: Simulation Model 2

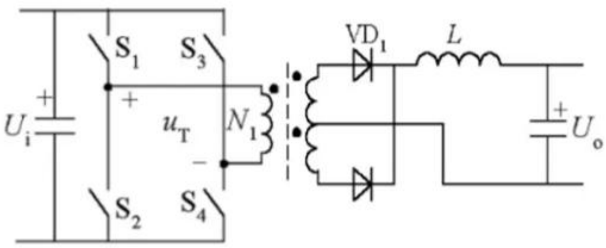
Based on topology shown in Figure 14, we established the corresponding simulation model.

3. Parameter Setup

3.1 Major Parameter

T	Vin	Vo	RL	fs	L	C
6:1:1	800V	50V	20ohm	100kHz	600μH	200μF

3.2 Calculation of Duty Cycle

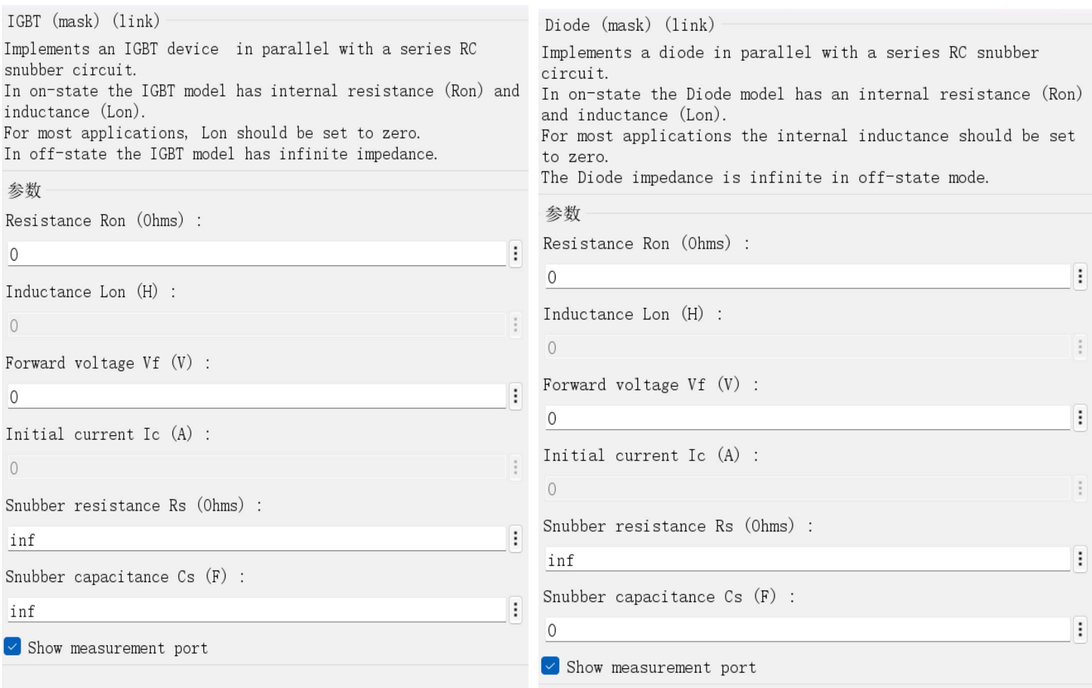


According to Volt-second balance of the inductor. We can see that:

$$\left(\frac{N_2}{N_1}U_i - U_o\right)t_{on} - U_o\left(\frac{T}{2} - t_{on}\right) = 0$$

$$D = \frac{t_{on}}{T} = \frac{U_o}{2U_i}\frac{N_1}{N_2} = 0.1875$$

3.3 Device Parameter


IGBT (mask) (link)
Implements an IGBT device in parallel with a series RC snubber circuit.
In on-state the IGBT model has internal resistance (Ron) and inductance (Lon).
For most applications, Lon should be set to zero.
In off-state the IGBT model has infinite impedance.
参数
Resistance Ron (Ohms) :
0
Inductance Lon (H) :
0
Forward voltage Vf (V) :
0
Initial current Ic (A) :
0
Snubber resistance Rs (Ohms) :
inf
Snubber capacitance Cs (F) :
inf
Show measurement port

Diode (mask) (link)
Implements a diode in parallel with a series RC snubber circuit.
In on-state the Diode model has an internal resistance (Ron) and inductance (Lon).
For most applications the internal inductance should be set to zero.
The Diode impedance is infinite in off-state mode.
参数
Resistance Ron (Ohms) :
0
Inductance Lon (H) :
0
Forward voltage Vf (V) :
0
Initial current Ic (A) :
0
Snubber resistance Rs (Ohms) :
inf
Snubber capacitance Cs (F) :
0
Show measurement port

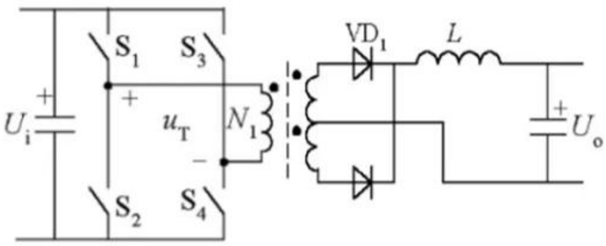
Figure 16: Parameter of Full-bridge IGBT Switch (L) and Rectifier Diode(R)

It is noticed that the switches of the converter are all ideal ones.

Figure 17: Parameter of Transformer (L) and Pulse Generator (R)

4. Simulation Results

4.1 Operating Principle and Sequence



This circuit is a double-ended indirect DC to DC chopper, which is composed of a full-bridge inverter, a full-wave rectifier and an isolation transformer. There are four states of this converter, which will be illustrated in the following part. It is noticed that the state of switch S1 and S4 is the same, so does S2 and S3, which means the inverter switch conducts in a diagonal manner. The upper switch and lower switch conduct alternately to generate AC output value to the primary side of the transformer.

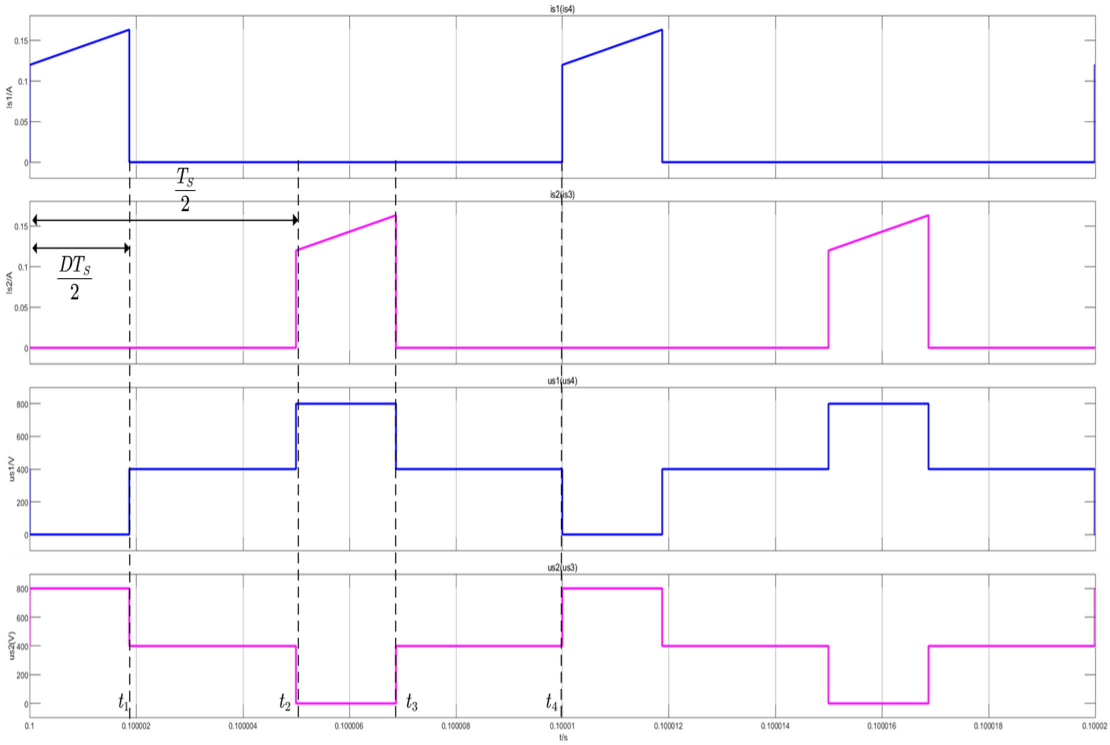


Figure 18: Waveform of inverter switch current and voltage

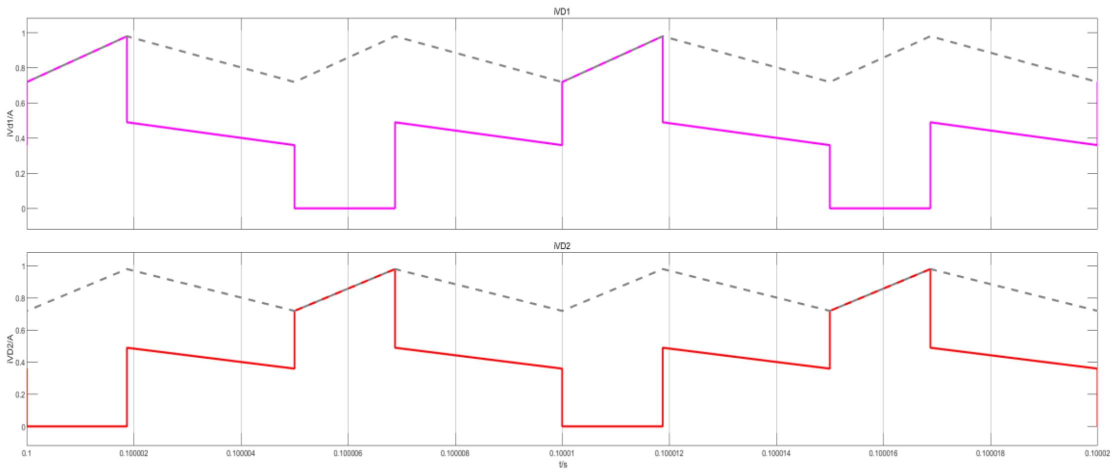


Figure 19: Waveform of Rectifier diode current (dotted line: load inductor current)

State	S1(S4)	S2(S3)	VD1	VD2
t0~t1	on	off	on	off
t1~t2	off	off	on	on
t2~t3	off	on	off	on
t3~t4	off	off	on	on

It is noticed that state2 and state 4 is the same. All the inverter switches are off at this state. Due to the magnetic balance equations of the transformer, if we ignore the filed current to be zero, we can see that the two secondary sides will generate current flowing through reverse direction. Therefore, both diodes can be conducted.

4.2 CCM and DCM Mode

4.2.1 Critical Resistor

We all know that the CCM and DCM Mode mainly focus on the state of the inductor current. Therefore, we can assume that the lowest point of the inductor current is just zero.
In this way:

$$I_{L\max} = 2\frac{U_o}{R}$$

When the inductor is discharging:

$$\frac{U_o}{L}\left(\frac{T}{2} - DT\right) = I_{L\max}$$

Then, we can get the critical resistor:

$$R_{Critical} = \frac{4L}{(1-2D)T} = 384\Omega$$

4.2.2 Simulation Results

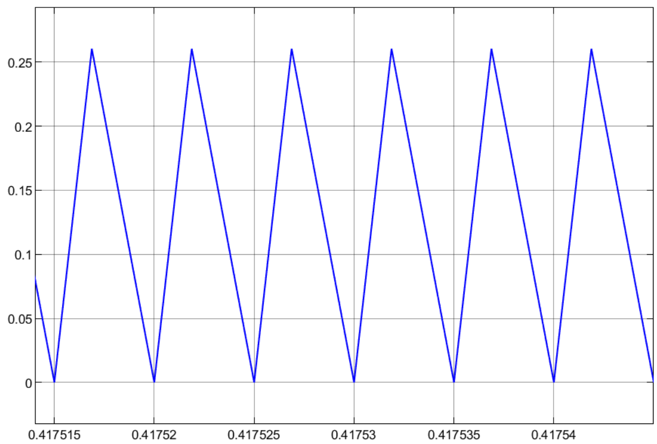


Figure 20: Inductor current when RL =384 ohm (Critical State)

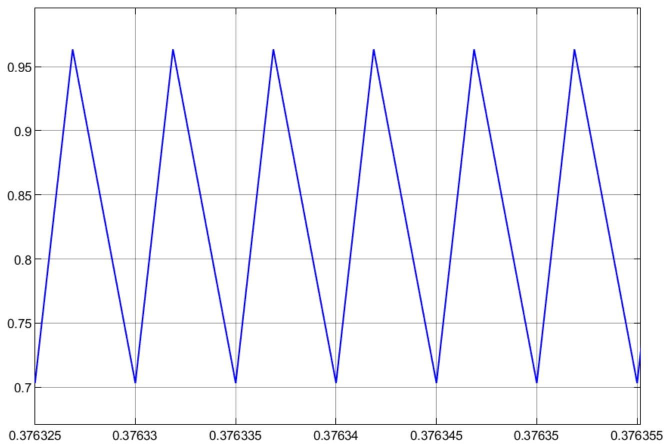


Figure 21: Inductor current when RL =60 ohm (CCM)

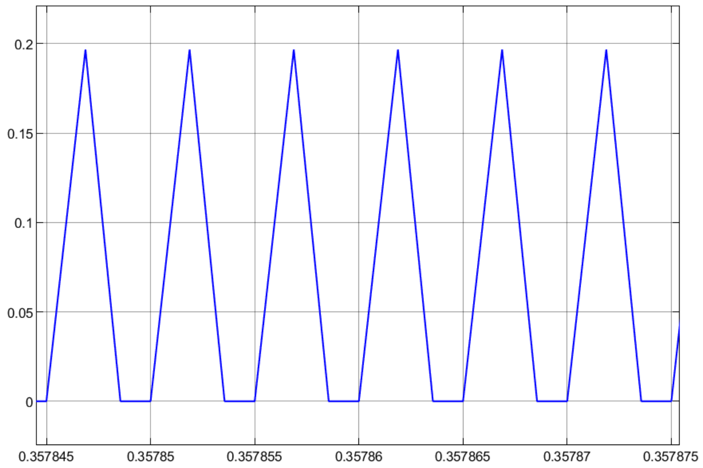


Figure 22: Inductor current when RL =1000 ohm (DCM)

Based on the waveform of inductor current, we can clearly verify the conclusions.

4.3 Relationship between Duty Cycle D and Voltage Gain

4.3.1 Calculation of Voltage Gain

When it is CCM Mode, based on previous equation:

$$D = \frac{t_{on}}{T} = \frac{U_o}{2U_i}\frac{N_1}{N_2} = 0.1875$$

We can see:

$$G = \frac{2N_2}{N_1}D$$

However, when it is DCM Mode, the equation above just does not work any more.

When the inductor is charging, we can know:

$$\frac{\frac{N_2}{N_1}U_i - U_o}{L}t_{on} = \frac{2U_o}{R}$$

$$G = \frac{\frac{N_2}{N_1}D}{2Lf_s/R + D}$$

When:

$$D = \frac{1}{2} - \frac{2L}{RT}$$

The circuit is transferred from DCM to CCM.

4.3.2 MATLAB Program

Similar to Topic 1, as duty cycle is variable, we write a program correspondingly, calculate the voltage gain and generate the plots.

clc;clear;

```
N=46;k=1;
Uin=800; %输入电压为 200V
Uout=zeros(1,N); %输出电压
G=zeros(1,N); %  电压增益

%%  模型调用
tic %计时模块
for D=0.01:1:45.01
      out=sim('m2',[0,0.3]);
      Uout(k)=out.Uo.Data(end);
      G(k)=Uout(k)/Uin;
      fprintf('循环第%d 轮\n',k);
      k=k+1;
end
toc

load G_CCM.mat
load G_DCM.mat
clf;
%%  数据制图
d=0.01:1:45.01;
figure(1)
plot(d,G_CCM,'b-');
xlabel('$D/\%$','Interpreter','latex');
ylabel('$G$','Interpreter','latex');
title('$G=f(D)$','Interpreter','latex');

figure(2)

d=0.01:1:45.01
plot(d,G_CCM,'b-');
hold on
plot(d,G_DCM,'r-');
xlabel('$D/\%$','Interpreter','latex');
ylabel('$G$','Interpreter','latex');
title('$G=f(D)$','Interpreter','latex');
legend('$G_{CCM}$','$G_{DCM}$','Interpreter','latex');
```

4.3.3 Simulation Results

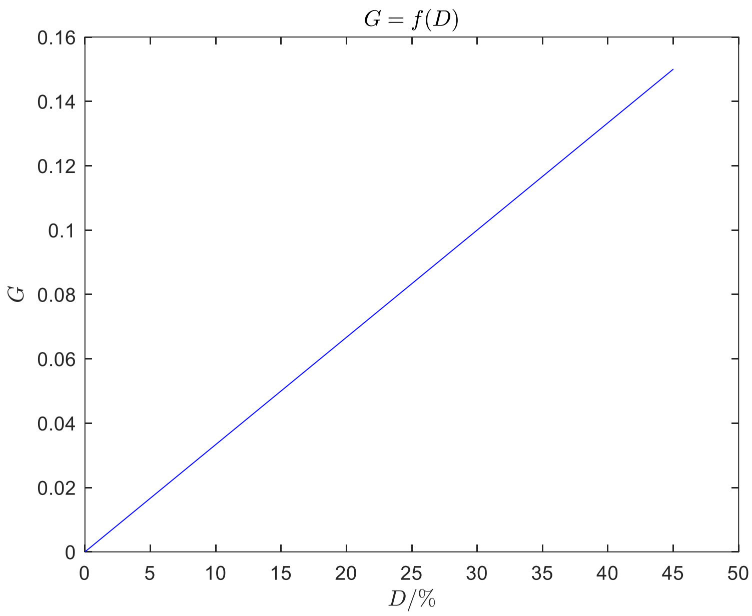


Figure 23: Relationship between voltage gain and D (R=60ohm)

When the load resistor is 60 ohm, we can see the whole circuit always works under CCM mode.

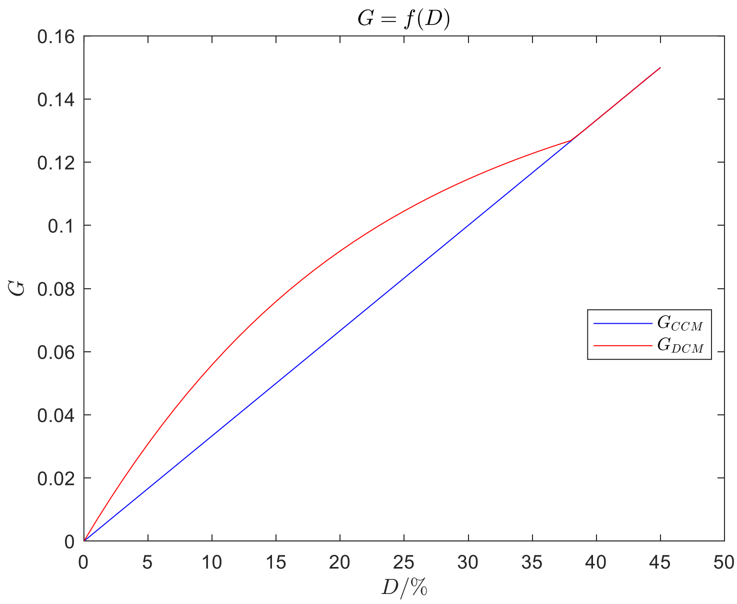


Figure 24: Relationship between voltage gain and D (R=1000ohm red ,R=60 ohm blue)

When the load resistor is rather large, we can see there exists DCM mode. When D is larger than 0.38, the circuit reaches CCM mode.