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EE 296 Master Project Report
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Design and Simulation of High Frequency Switched Mode Power Supply

Abstract

A high frequency switched mode power supply is designed with adjustable voltage and current in this project. Throughout the process of designing, a combination of theoretical analysis and MATLAB simulation research method is used. Firstly, according to the working principle and control mode of full bridge DC-DC converter, analyzing the full-bridge phase-shifted topology structure and working principle. Then, according to the design requirements to design the main circuit, control circuit and drive circuit. The project uses IGBT as the power switch device to form a three-phase full bridge converter. It uses pulse width modulation (PWM) technology to obtain control signal from the integrated chip and output the real-time voltage sampling signal to control the changes of voltage output and current output. Finally, modeling and simulating with MATLAB. It includes building mode on the Simulink system platform, setting simulation parameters and analyzing the steady-state and transient performance by the simulation waveforms.

1 Introduction

1.1 The advantage of Switched Mode Power Supply

A switch mode power supply is an electronic power supply that incorporates a switching regulator to convert electrical power efficiently. Unlike a linear power supply, the pass transistor of a switching-mode supply continually switches between low-dissipation, full-on and full-off states, and spends very little time in the high dissipation transitions, which minimizes wasted energy. Ideally, a switched-mode power supply dissipates no power. Voltage regulation is achieved by varying the ratio of on-to-off time. This higher power conversion efficiency is an important advantage of a switched-mode power supply. Switched-mode power supplies also be substantially smaller and lighter than a linear supply due to the smaller transformer size and weight.

1.2 The content of the project

a. The working principle of high frequency switched mode power supply (AC input voltage goes through the EMI filter and rectifier filter to get DC voltage. Then, it goes through the inverter to get high frequency AC voltage. Finally, it goes through the output rectifier filter to get the required DC output voltage).

b. The design of main circuit high with IGBT full bridge converter.

c. The design of control circuit with Pulse Width Modulation.

d. The MATLAB simulation.

2 Working Principle and Scheme Selection

2.1 The working principle of high frequency switched mode power supply

High frequency switched mode power supply is the equipment to convert AC input (single-phase or three-phase) voltage to a required DC voltage. [1] The block diagram of basic isolated high frequency switched power supply is shown in Figure 2-1, it consists of EMI Filter, Input Rectifier and Filter, High Frequency Converter and Transformer, Output Rectifier and Filter, Control Circuit and Assistant Power.

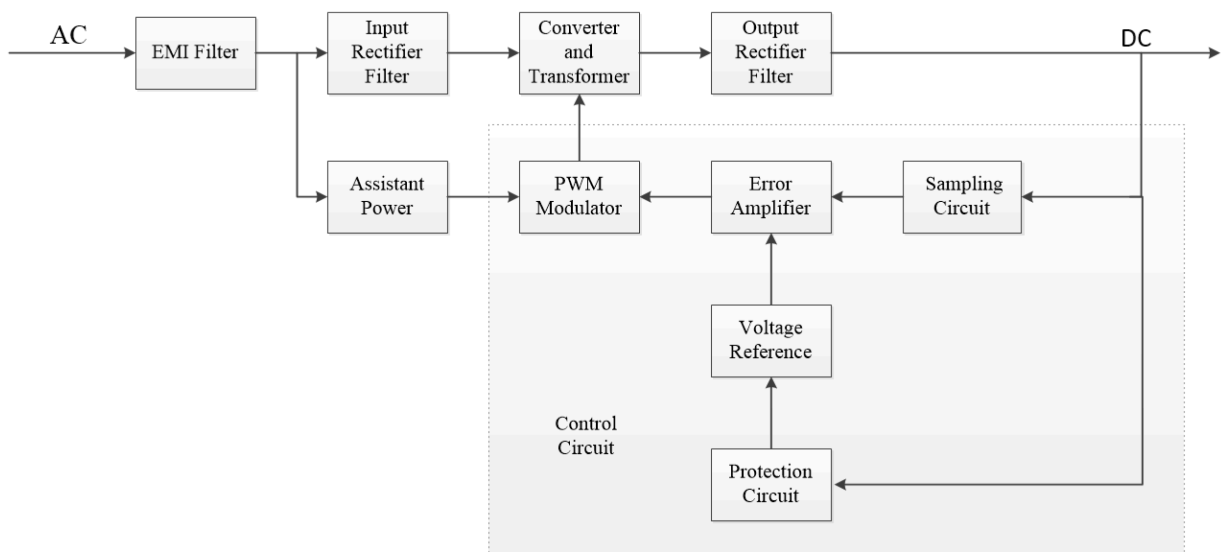


Figure 2-1

a. EMI Filter: It's an electronic passive device which is used in order to suppress conducted interference that is present on a signal or power line. [2] EMI filters can be used to suppress interference that is generated by the device or by other equipment in order make a device more immune to electromagnetic interference signals present in the environment. Most EMI filters consist of components that suppress differential and common mode interference. The classical EMI filter is shown as Figure 2-2:

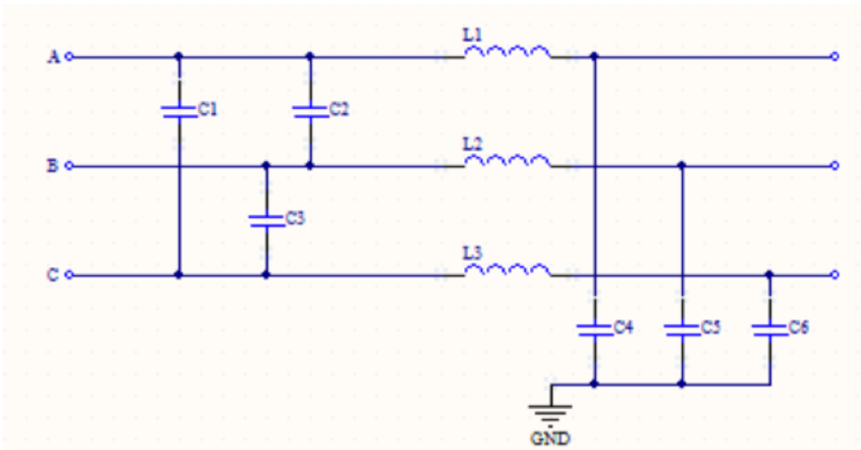


Figure 2-2

b. Input Rectifier and Filter: It rectifies and filters the the AC voltage form the input, and offer the DC voltage to converter. For the three-phase input, its classical rectifier and filter circuit is shown as Figure 2-3:

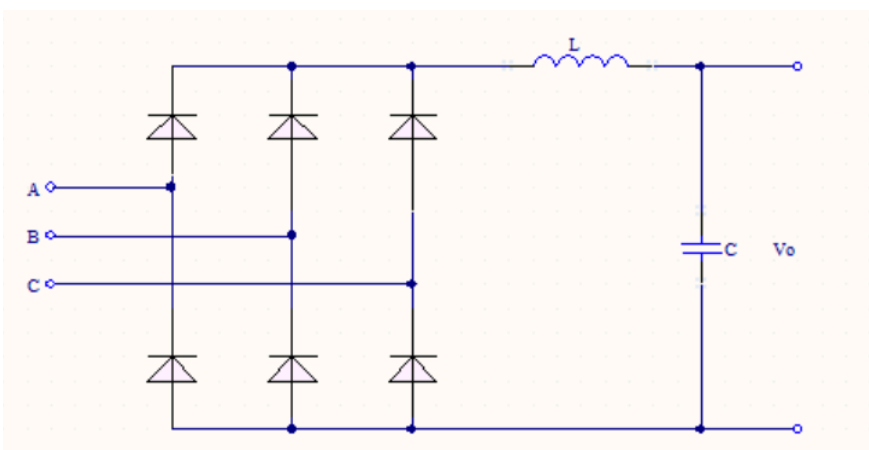


Figure 2-3

c. High Frequency Converter: It's the key component of switch power supply. It converts the DC voltage to high frequency AC voltage and then it goes through the high frequency transformer to get the required AC voltage.

d. Output Rectifier and Filter: It rectifies and filters the the AC voltage form the converter and get the required DC voltage.

e. Control Circuit: It checks the DC voltage and compare with voltage reference to get the stable voltage output from the converter.

2.2 The selection of converter

The isolated DC switch converter can be classified as:

a. Flyback converter

The flyback converter is used in both AC/DC and DC/DC conversion with galvanic isolation between the input and any outputs. The flyback converter is a buck-boost converter with the inductor split to form a transformer, so that the voltage ratios are multiplied with an additional advantage of isolation. [3] The main circuit of flyback converter is shown as Figure 2-4:

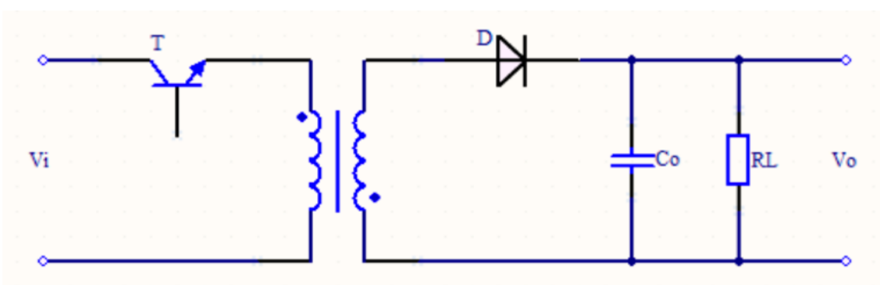


Figure 2-4

b. Forward converter

The forward converter is a DC/DC converter that uses a transformer to increase or decrease the output voltage and provide galvanic isolation for the load. The forward converter does not store energy during the conduction time of the switching element. Instead, energy is passed directly to the output of the forward converter by transformer action during the switch conduction phase. [4] The main circuit of forward converter is shown as Figure 2-5:

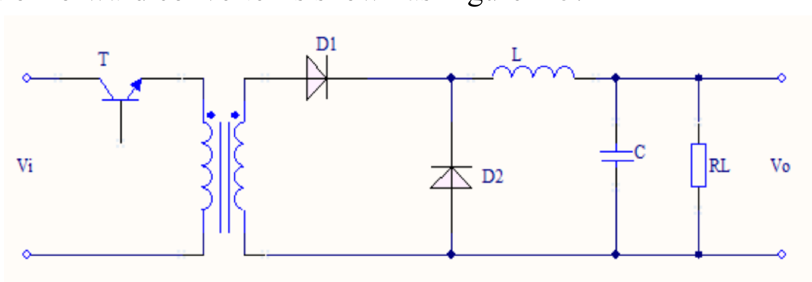


Figure 2-5

c. Full-bridge converter

The full-bridge converter adds two additional transistors to the half-bridge converter. Figure 2-6 shows the schematic of the full-bridge converter. One advantage of the full-bridge converter is that it only requires one capacitor for smoothing the output voltage, whereas the half-bridge converter required two. The full-bridge converter will be used in larger power supplies usually over 1000 Watts. Because our power supply has 22V, 200A with total power 4.4KW, so we select the full-bridge converter.

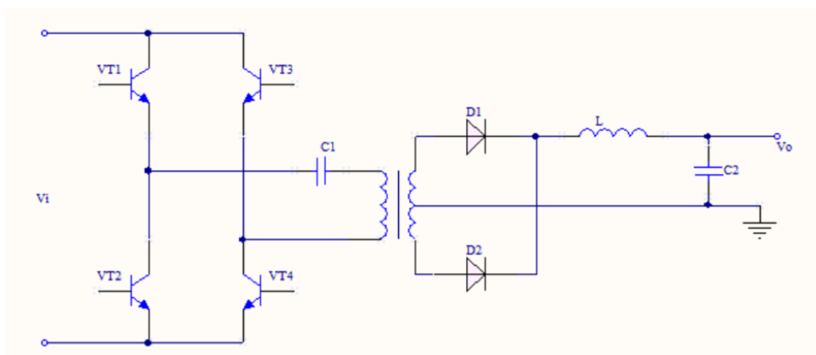


Figure 2-6

2.3 Control circuit

In this project, we select PWM to implement the control circuit. Pulse-width modulation is a modulation technique used to encode a message into a pulsing signal. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there being practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, thus in both cases close to zero. The block diagram of PWM is shown as Figure 2-7

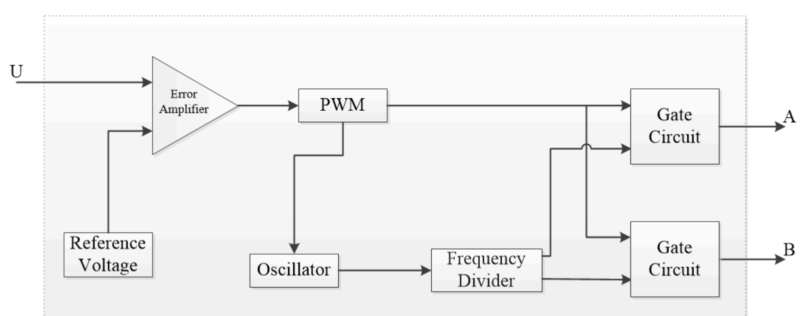


Figure 2-7

3 Phase-shifted Full Bridge Conversion Technology

3.1 Phase-shifted Full Bridge ZVS-PWM Conversion Circuit

Due to its high power output, full bridge circuit is often used in a variety of high-power conversion circuits. In the hard switching PWM full bridge circuit, the output equivalent capacitance of the switch devices, the primary side of the transformer leakage inductance and circuit lead inductance will increase switching losses. If we use ZVS-PWM conversion technology for full-bridge inverter circuit, it will be easy to solve several problems at hard switching PWM converter. Phase-shifted Full Bridge ZVS-PWM circuit is shown as Figure 3-1:

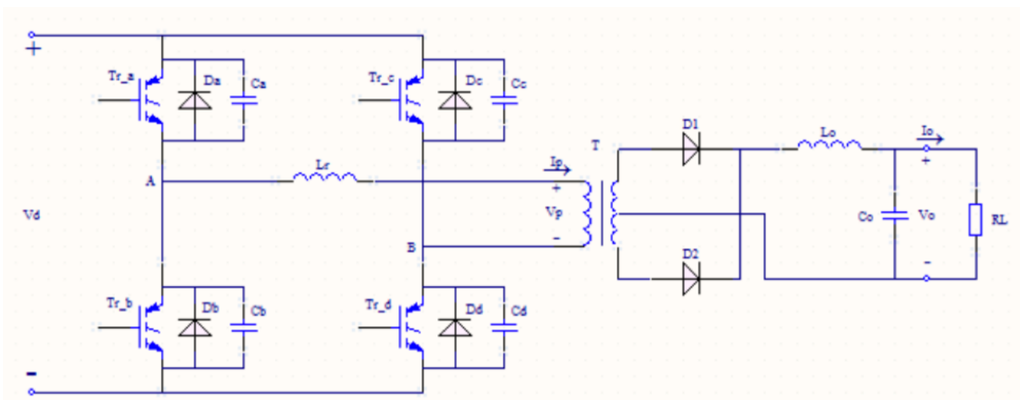


Figure 3-1

In Figure 3-1, there are four switches $\mathrm{Tr_a}$~$\mathrm{Tr_d}$, $D_a \sim D_d$ are their anti-parallel diodes and $C_a \sim C_d$ are their output equivalent capacitance. L_r is a resonant inductor, including transformer's primary leakage inductance. T is the ideal inverter transformer. [5]

Different with hard switching PWM, and the bridge arm switch is not completely and simultaneously turn on and off for $\mathrm{Tr_a}$ and $\mathrm{Tr_d}$ or $\mathrm{Tr_b}$ or $\mathrm{Tr_c}$, and instead of using phase shift control technology, the turn on sequence is in Table 3-1.

Table 3-1 The turn on sequence of switches and diodes

Stage	1	2	3	4	5	6
Turn on	Tr_a,Tr_d	Tr_a	Tr_a,Dc	Tr_a,Tr_c,Dc	Tr_c,Dc	Tr_c,Dc,Db
Stage	7	8	9	10	11	12
Turn on	Tr_b,Tr_c	Tr_b	Tr_b,Dd	Tr_b,Tr_d,Dd	Tr_d,Dd	Tr_a,Da,Dd

From the table above, at any period, four switches $\mathrm{Tr_a}$~$\mathrm{Tr_d}$ will not all ended at the same time, but they will one by one in order to turn on and off, so that they are mutually auxiliary switch to achieve zero voltage switching.

3.2 Phase-shifted Full Bridge ZVS-PWM Conversion Features

a. If the inductor is large enough and load is not too small, four switches in the inverter bridge can achieve zero-voltage switching and switching loss will be small.

b. In every energy transfer process, it's always the switches(Tr_c and Tr_d) on right bridge leg turn off first to the terminal voltage conversion. We call the right bridge leg as the leading leg and left bridge leg as lagging leg. Note that, the bridge leg is leading or lagging is decided by driver's timing signal. Since I_p is large when leading leg does voltage conversion, and the excitation energy participate in, so it is easy to achieve zero-voltage switching, the condition is as following:

$$(L_r + L_m)\times(I_o/n)^2 > (4C/3 + C_t/2) \tag{3-1}$$

c. When lagging leg switch tube does voltage converter, it has no excitation energy, only the stored energy in L_r. To achieve zero-voltage switching in Tr_a or Tr_b , it needs to meet the following condition:

$$L_r\times I_1^2/2 > (4C/3 + C_t/2)V_d^2 \tag{3-2}$$

4 Main Circuit Design

4.1 High Frequency Transformer Design

In general, the design of the transformer [6] can follow the steps below:

a. Determine the main circuit topology and operating frequency.

According to the output capacity of the transformer, we can basically determine the topology of the main circuit and the frequency of inverter switching.

b. Calculate the transformer turns ratio

The transformer turns ratio n refers to ratio of primary turns N_1 and secondary turns N_2, where $n = N_1/N_2$. Determine the transformer turns ratio must ensure that the minimum input voltage can output the desired maximum voltage V_{omax}, at this time, the inverter operates at maximum duty cycle D_{max}. Minimum input voltage V_{imin} determines the minimum voltage V_{1min} from transformer primary side, and then the transformer secondary voltage V_{2min} is the lowest, these parameter should be satisfied with the following relationship:

$$V_{2min} = \left(V_{omax} + V_f + V_x\right)/D_{max} \tag{4-1}$$

where, V_f is output rectifier voltage drop and V_x is voltage drop on the output winding resistance.

c. Determine current density coefficient j

According to the operating frequency, take full account of the skin effect, transformer cooling conditions and allowed temperature rise, select the appropriate wire current density j.

d. Estimate area product A_eA_w of iron core

Using the following formula to calculate the A_eA_w:

$$A_eA_w = \left[\frac{P_o\times(1+\eta)\times 10^4}{\eta K_o K_c f B_m j}\right]^{1.14} \tag{4-2}$$

where, A_e is iron core cross-sectional area(cm^2), A_w is iron core window area (cm^2), P_o is Transformer output power(W), η is transformer efficiency, K_c is the effective utilization coefficient of the window, K_c is scaling factor, f is switching frequency(H_z), B_m is operating flux density of iron core(T) and j is current density coefficient.

e. Calculate the winding turns

For double-ended transformer, primary winding turns can be calculated by the formula (4-3):

$$N_1 = \frac{V_{1max}}{K_o\times f\times A_e\times B_m} \tag{4-3}$$

f. Calculate wire's cross-sectional area

Primary and secondary wire cross-section are as follows:

$$S_1 = I_1/j \tag{4-4}$$

$$S_2 = I_2/j \tag{4-5}$$

g. Calculate window occupancy factor K_c'

$$K_c' = (S_1N_1 + S_2N_2)/A_w \tag{4-6}$$

Note that K_c' should small than K_c and if there are several windings, SN should be accumulated.

4.2 High Frequency Inverter Transformer Parameter Calculation

The main circuit is shown as Figure 4-1

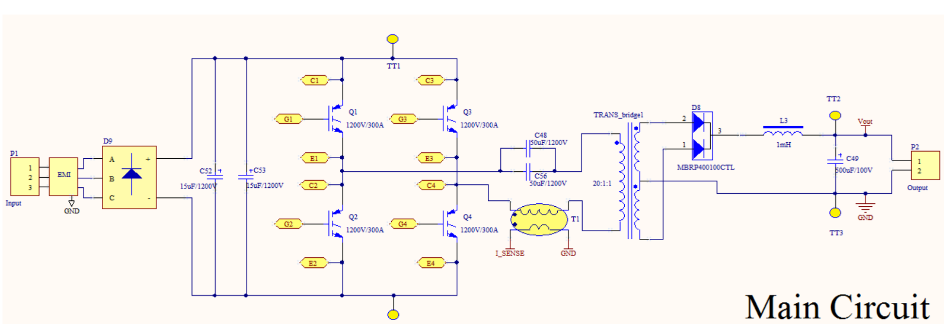


Figure 4-1

a. Range of DC bus voltage calculation

AC input voltage is 480V, three-phase full-bridge rectifier has six first waves per cycle (20ms). Therefore, the range of DC bus voltage is that:

$$V_{dmax} = 480\times\sqrt{2} \approx 679V$$

$$V_{dmin} = 480\times\sqrt{2}\times \sin 60 \approx 588V$$

b. Secondary voltage and the minimum duty cycle

Assume the voltage drop of rectifier diode is 1V, the wire voltage drop and the secondary winding resistance voltage drop is 2V, the maximum duty cycle is 0.85, the minimum voltage of the transformer secondary output is that:

$$V_{2min} = \left(V_{omax} + V_f + V_x\right)/D_{max}$$

$$= (22 + 1 + 2)/0.85 \approx 29.41\mathrm{V}$$

$$D_{min} = \frac{V_{dmin}\times V_{omin}}{V_{dmax}\times V_{omax}}\times D_{max}$$

$$= \frac{588\times 10}{679\times 22}\times 0.85 \approx 0.33$$

c. Transformer turns ratio

The design of transformer turns ratio needs to ensure that the minimum input voltage can get the required output V_{2min}.

$$\mathrm{n} = \frac{N_1}{N_2} = \frac{V_{dmin}}{V_{2min}} = \frac{588}{29.41} \approx 19.9 \approx 20$$

d. Iron core dimension calculation

Assume B_m=0.15T， K_c=0.4， $\mathrm{j} = 2.5\times 10^4 A/m^2$, according to formula (4-2), we can estimate iron core dimensions:

$$A_e A_w = \left[\frac{P_o\times(1+\eta)\times 10^4}{\eta K_o K_c f B_m j}\right]^{1.14}$$

$$= \left[\frac{4560\times(1+0.985)\times 10^4}{0.985\times 4\times 0.4\times 20\times 10^3\times 0.15\times 250}\right]^{1.14}$$

$$\approx 135 cm^2$$

e. Transformer turns calculation

According to formula (4-3), we can calculate primary turns N_1

$$N_1 = \frac{V_{1max}}{K_o\times f\times A_e\times B_m}$$

$$= \frac{679}{4\times 20\times 10^3\times 27.2\times 10^{-4}\times 0.15} \approx 20.8$$

and secondary turns is $N_{21} = N_{22} = N_1/20 \approx 1.04$, Adjust the number of turns, take the secondary turns as $N_{21} = 1$ and the primary turns $N_1 = 20$.

4.3 Output rectifier filter circuit

a. Selection of output rectifier diode

Output current is $I_0 = 200A$, the current rating of the rectifier diode should be 300 ~ 400A, the highest voltage of transformer secondary winding is $V_{2max} = V_{1max}/n = 679/20 \approx 34V$, considering the reverse recovery voltage spikes, the output rectifier diode voltage should not be lower than 50V, so we can select 100V.

b. Output filter parameters calculation

$$V_2 = V_{2m} = V_{1max}/n = 679/20 \approx 34\text{A}$$
$$T_{on} = D'_m \times T/2 = 0.5 \times 50/2 = 12.5\mu s$$

At this time, if the requested change of inductor current is 1A during T_{on} (inductor's continuous current when 5% rated load), where $\Delta i_L = 1A$, according to the following formula :

$$\text{L}_{on} = \frac{(V_{2m} - V_o) \times T_{on}}{\Delta i_L} = \frac{(33.6 - 22) \times 12.5\mu}{1} = 0.145\text{mH}$$
$$\text{L}_{off} = \frac{V_o \times T_{off}}{\Delta i_L} = 0.825mH$$

So we choose $L = 1mH$.

$$\text{C} = \frac{\Delta i_L \times T}{8 \times \Delta u_c} = \frac{1A \times 50\mu s}{8 \times 20mV} \approx 313\mu F$$

Thus, we choose $500\mu\text{F}, 100\text{V}$ electrolytic capacitor.

5 Control Circuit Design

5.1 Introduction of control chip

UCC3895 is mainly used in full-bridge phase-shifted and soft-switching PWM circuit. [7] It can be used for single voltage loop feedback control model and peak current control model. Especially in peak current mode, the primary bus current obtained from the current transformer by isolation collection, and the signal goes through the filter and slope compensation circuit to obtain current control signal; On the other hand, the output voltage signal after adjustment and isolation, and then compare with voltage reference to obtain voltage control signal. The current and voltage control signal input phase-shifted PWM controller UCC3895 to get four PWM control signal via a chip comparator and a pulse generating circuit.

5.2 Voltage feedback control design

The output voltage feedback circuit using TL431 and PC817 to cooperate with each other as a reference, isolation, sampling.

The TL431 is three-terminal adjustable shunt regulators, [8] with specified thermal stability over applicable automotive, commercial, and military temperature ranges. The output voltage can be set to any value between Vref (approximately 2.5 V) and 36 V, with two external resistors.

PC817is a universal optocoupler, it can transmit continuous change analog voltage or current signal and produce the corresponding light signal, so that the level of conduction of the phototransistor is different, voltage or current output will also be different.

5.3 Drive circuit design

In this project, the drive circuit utilizes driver chip M57962L, The M57962L is a Hybrid Integrated Circuit for driving N-channel IGBT modules in any gate amplifier application. This device operates as an isolation amplifier for these modules and provides the required electrical isolation between the input and output with an opto-coupler. Short-circuit protection is provided by a built in desaturation detector. A fault signal is provided if the short-circuit protection is activated.

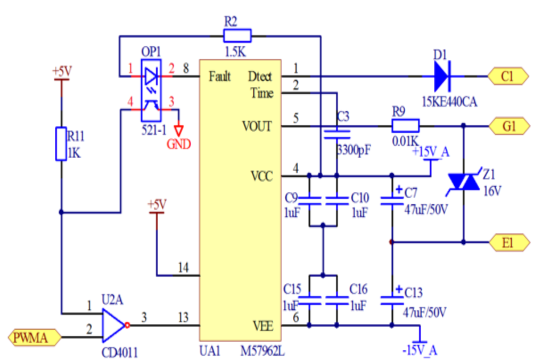


Figure 5-1

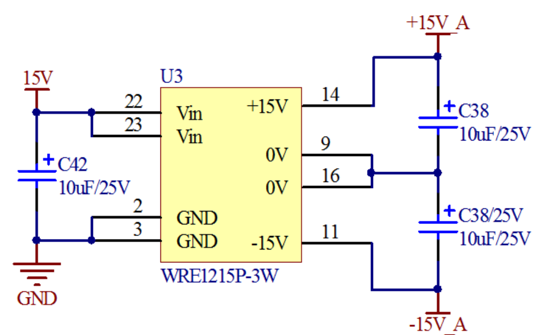


Figure 5-2

5.3 Drive power design

Drive power utilizes WRE1215P-3W series DC / DC voltage isolation module. According WRE1215P-3W features, use this module not only ensures the safety and reliability of the circuit, but also the driving circuit power supply design is very compact. Driving power supply circuit shown in Figure 5-2

6 Modeling and simulation

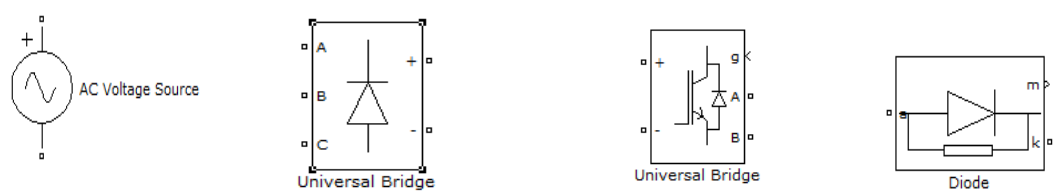
6.1 Introduce of MATLAB

MATLAB (matrix laboratory) is a multi-paradigm numerical computing environment and fourth-generation programming language. MATLAB provided "SimPowerSystems" toolbox which is the ideal tool for power electronics system simulation. It’s different with simulation of PSPICE and other simulation software focus on device level, it’s more concerned about the external characteristics of the device and easy to connected with the control system. SimPowerSystems model library contains commonly used power modules, using these modules can simplify the description of electric system. [9]

6.2 Simulation model design

a. Design the main circuit of simulation model

Select AC voltage source module from "Electrical Sources" library of SimPowerSystem, as shown in Figure 6-1(a), the parameters are set as follows: AC voltage to 392V, rated frequency 60HZ, voltage can be measured. Then select "Universal Bridge" module from "Power Electronic" library as three-phase full-bridge uncontrolled rectifier bridge, shown in Figure 6-1(b), the parameters are set as follows: two pairs of leg, a buffer resistor $R_s = 10^5\Omega$, snubber capacitor $C_s = 10^{-6}$F, select diode as power device, its forward voltage drop is $V_f = 0$V. [10]



(a) (b) (c) (d)

Figure 6-1

Similarly, select "Universal Bridge" module from "Power Electronic" library as a controllable three-phase inverter bridge, shown in Figure 6-1(c), the parameters are set as follows: two pairs of leg, a buffer resistor $R_s = 10^5\Omega$, snubber capacitors $C_s = 10^{-6}$F, electrical installations Select IGBT $R_{on} = 10^{-3}\Omega$, $T_f = 10^{-6}s$, $T_t = 2\times10^{-6}s$. Select "Power Elements" in "Diode" module, as a rectifier diode, as shown in Figure 6-1(d), the parameters are set as follows: forward voltage of 0.8V, the snubber resistor, snubber capacitor. Select the resistive load in "Elements" library, which can be measured voltage and current.

b. Design the control subsystem of simulation model

Control subsystem architecture shown in Figure 6-2. Output voltage U is compared with a reference voltage U*, through continuous commissioning to get optimal PI controller to meet the requirements of the PWM output wave.

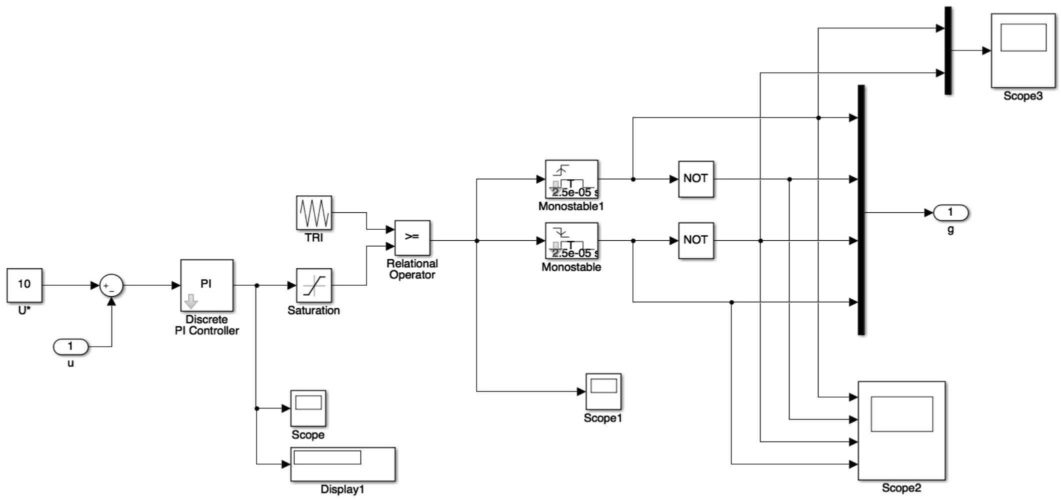
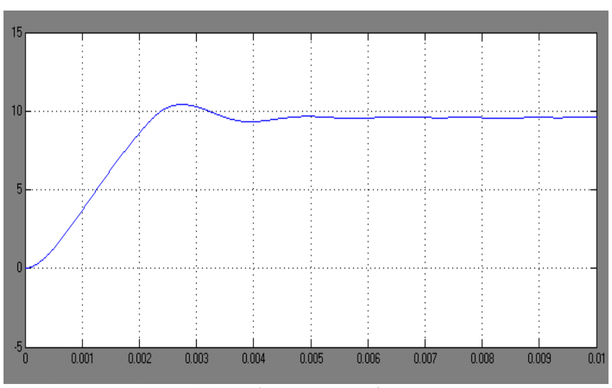


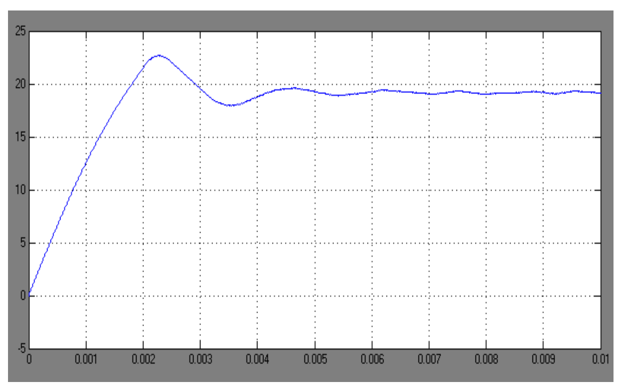
Figure 6-2

6.2 Result of Simulation

a. When the reference voltage U* = 10V,



(a) Voltage waveform

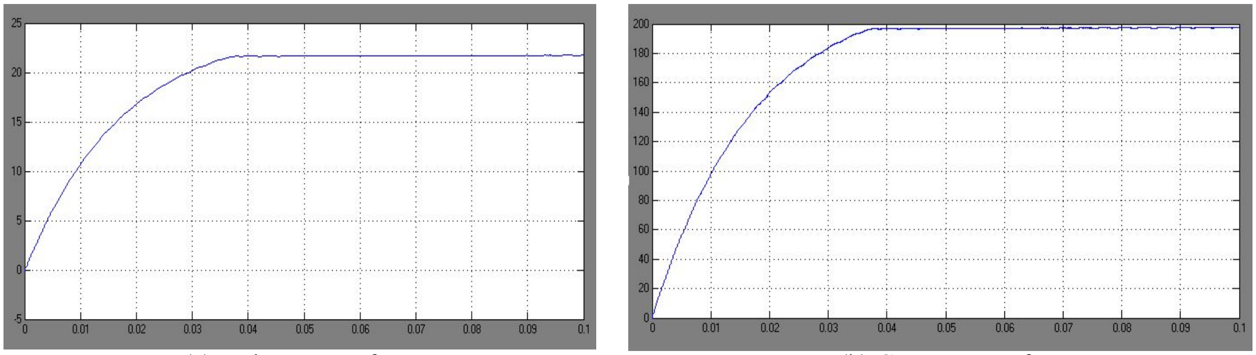


(b) Current waveform

Figure 6-3

As the Figure6-3 shows above, the output voltage U_o has a gradual upward trend form zero, after reaching the peak of about 10.8V, it decreases to 10V and has oscillation, eventually it stabilizes at around 10V; output current I_o also has a gradual upward trend from zero, after reaching the peak of 23A, it has the downward trend and decreases to 20A and has oscillation, eventually stabilizes at around 20A.

b. When the reference voltage U* = 22V



(a) Voltage waveform (b) Current waveform

Figure 6-4

As shown in Figure 6-4 above, the output voltage U_o has a gradual upward trend form zero, after about 0.037s, it eventually it stabilizes at around 22V; output current I_o also has a gradual upward trend from zero, after about 0.038s, it finally stabilizes at around 200A.

7 Conclusion

Through the study of the basic principles of high-frequency switching power supply and a comparative analysis of the various switching converter topologies, we design a high-frequency switching power supply that has light weight, small size, high efficiency features. In order to improve the performance of switching power supply, we should can do further research in the following areas:

a. Monitoring unit design: Use the system monitor module as a stand-alone module that can monitor the status of the whole power system. It has functions of acquisition, display and setting system operating parameters. Select chip AT89C52 as the core monitoring unit to achieve overvoltage protection, overcurrent protection, phase, voltage and fault warning lamp functions.

b. Improving component parameter design of PSFB control circuit, adjusting parameters of voltage loop and current loop, so that the switching power supply can achieve better steady-state and dynamic performance.

Reference:

[1] Henry J. Zhang, Basic Concepts of Linear Regulator and Switching Mode Power Supplies, Linear Technology, Application Node, October, 2013

[2] Mohan, Ned, Undeland, Tore M., Robbins, William P., Power Electronics: Converters, Applications, and Design, Wiley, 2002

[3] Billings, Keith, Switch mode Power Supply Handbook (Second ed.), McGraw-Hill, 1999

[4] Rudy Severns, The History of the Forward Converter, Switching Power Magazine, July 2000

[5] Yungtaek Jang, Milan M.Jovanovic, Yu-Ming Chang, A New ZVS-PWM Full-Bridge Converter, IEEE Transactions on power electronic, September 2003

[6] Robert W. Erickson, Dragan Maksimovic, Fundamentals of Power Electronics 2nd Edition, Springer, January, 2001

[7] Texas Instruments, "BiCMOS Advanced Phase-Shift PWM Controller", June, 2013

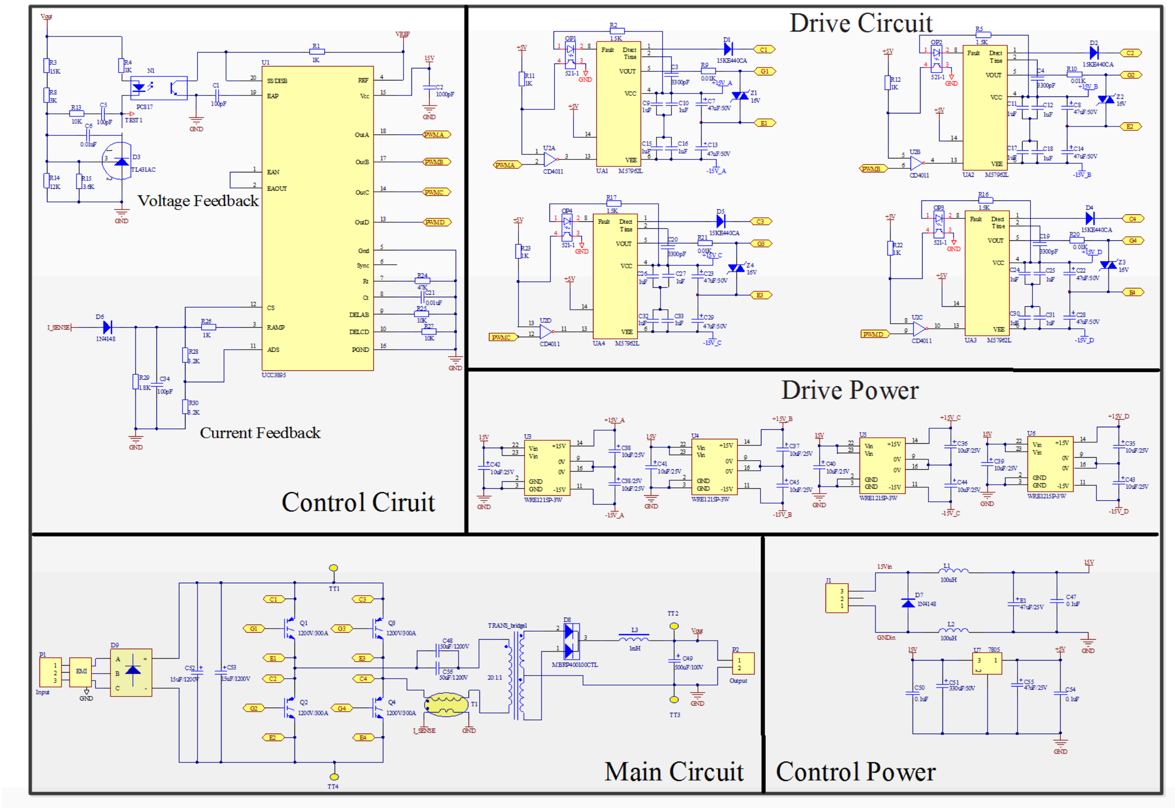
[8] Texas Instruments, "TL43xx Precision Programmable Reference", January 2015

[9] Viktor Perelmuter, Electrotechnical Systems: Simulation with Simulink and SimPowerSystems, CRC Press, October 2012

[10] Slobodan N. Vukosavic, Digital Control of Electrical Drives (Power Electronics and Power Systems), Springer, August 2007

Appendix:

a. **Circuit Schematic**



b. MATLAB Simulink block diagram