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Research of a High-Precision High-Power-Factor Switching Power Supply

*Zhi Cui, **Xianpu Cui

* School of Communication and Electronic Engineering, Hunan City University
China, No. 518, East Yingbin Road, Yiyang, (zhicui@yeah.net)
** School of Communication and Electronic Engineering, Hunan City University
China, No. 518, East Yingbin Road, Yiyang, (cuixianpu@sohu.com)

Abstract

We design a novel type of switching power supply which is an integration of flyback type and half-bridge resonant typology. Based on signal flow graph and division of functional modules of the circuit, we elaborate on the design principle, functions of different modules and working process of the switching power supply. By using three-terminal adjustable shunt regulator TL431, LD7535 and L6599, the voltage control of the power supply and voltage stabilizing are realized by regulating the pulse width and pulse frequency, respectively. The power factor is increased by adopting active power factor correction. Experiment shows that the switching power supply has good voltage stabilizing performance, with small ripple and high power factor as well as high voltage regulation and load regulation.

Key words

Switching power supply, fly back, half-bridge resonant typology, high precision

1. Introduction

Switching power supply is a DC voltage-stabilizing power supply which uses the switching regulator [1]. It regulates the output voltage by adjusting the switching frequency or duty cycle. Because of its small size, light weight and high frequency, the switching power supply is applied in nearly all electronic devices and plays an irreplaceable role in today's electronic information industry [2]. In the meantime, the requirement on the switching power supply is also rising in other new fields. Addressing the defects of low precision and low power factor in ordinary switching power supply, we design a novel type of switching power supply that is the combination of flyback type and half-bridge resonant typology. By designing closed-loop feedback control and employing active power factor correction, the precise control of the output voltage and the improvement of power factor are realized.

Switching power supply consists of input circuit, power factor correction circuit, pulse control circuit, power conversion circuit, output circuit, and feedback circuit. In our design, the first module is the input circuit. The 220V AC current passes through the protection circuit, EMI suppression filter and bridge rectifier, and the unstabilized DC voltage is obtained. This voltage is subject to power factor correction in the second module, which maintains the same phase between the input current and the input voltage. The third module is the power conversion circuit, which uses the switching tube to convert DC voltage into a pulse waveform with certain frequency and to transmit the energy to the output terminal. The fourth module is the output circuit, where the square wave pulse voltage is rectified, filtered and converted into DC voltage. The fifth module is the feedback control circuit, where the output voltage passes through the voltage divider and the sampler and is compared against the reference voltage and amplified. The feedback circuit incorporates the precision shunt regulator TL431 and optical coupler PC817C. Upon receiving the output voltage feedback, the control chip will output the pulse width modulation (PWM) signals, thus achieving high-precision voltage stabilizing.

2. Functional requirements and technical indicators

The purpose of this paper is to design a novel type of switching power supply which is an integration of flyback type and half-bridge resonant typology.

2.1 Efficiency and power factor of the power supply

Within the given range of input voltage and temperature, the table below presents the target range of output efficiency and power factor of the power supply. To calculate the overall efficiency, the output power is first obtained based on the product of output current and output voltage under the rated input voltage and output full load. Then the ratio of the output power to the input active power on the power meter is calculated as the overall efficiency. The power factor is the ratio of the input active power to the output apparent power [3].

2.2 Output voltage and current

Within the given range of input voltage and temperature, the table below presents the target values of output current, voltage, ripple and noise. Ripple is a component synchronized with the input frequency and switching frequency between the output terminals. Ripple is usually expressed as the peak-to-peak value and should be below 0.5% of the output voltage. Noise is another high-frequency component besides the ripple and should be about 1% of the output voltage [4].

Tab. 1 Efficiency and power factor of power supply

Input voltage	Output load	Efficiency	PF value
90VAC	rating	≧84%	≧98%
264VAC	rating	≧88%	≧93%

Tab. 2 Output voltage and current

	V1	V2	V3	V4
Output Voltage	+12V	+24V	+5V	+5Vsb
Peak Current	2.5A	5A	3.5A	1A
Rated Current	2A	4A	3A	0.5A
Voltage Regulation Factor	±5%	±5%	±5%	±5%
Ripple	60mV	180mV	30mV	30mV
Ripple and Noise	120mV	240mV	50mV	50mV

3. Detailed Process of Design

In this section, we will present the detailed process of design.

3.1 Input protection circuit

Input protection circuit consists of tube fuse, negative temperature coefficient (NTC) thermistor and voltage dependent resistor. When the power supply has just started up, NTC thermistor has low temperature and high resistance, offering instantaneous restraint to the charging current [5]. As the heat dissipated by the current increases, the resistance of NTC thermistor decreases rapidly. Thus NTC thermistor is started up and the power consumption is reduced.

Voltage dependent resistor absorbs the voltage surges from the grid, which are generated due to disturbances from the electrical equipments in the grid or natural lightning. Voltage surges can take place within a very short time and reach very high values, causing the fuse and other components in the power supply to burn out. Therefore, it is necessary to apply the voltage dependent resistor across the two ends of the input voltage, so as to divide and absorb the voltage and to protect the circuit.

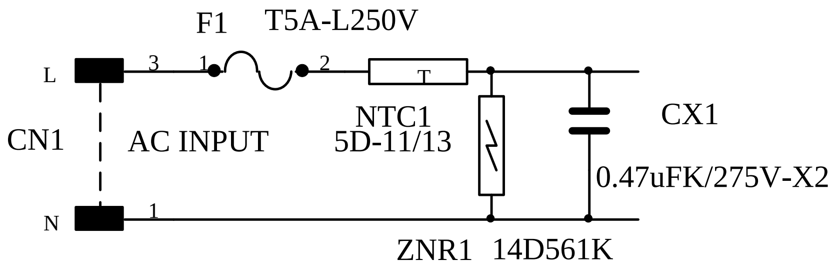

Fig.1. Input protection circuit

3.2 EMI suppression filter

EMI. suppression filter is usually designed with a common mode inductor and a filter capacitor. Common mode inductor is composed of two winding resistors with equal inductance in a closed magnetic circuit [6]. The phase difference is 180 degrees due to the magnetic flux generated by the frequency components of the power supply. Since the two resistors have equal number of windings, they counteract each other and the inductance of the frequency components of the power supply is zero. However, for the common mode noise, the effective permeability is very high, leading to large attenuation.

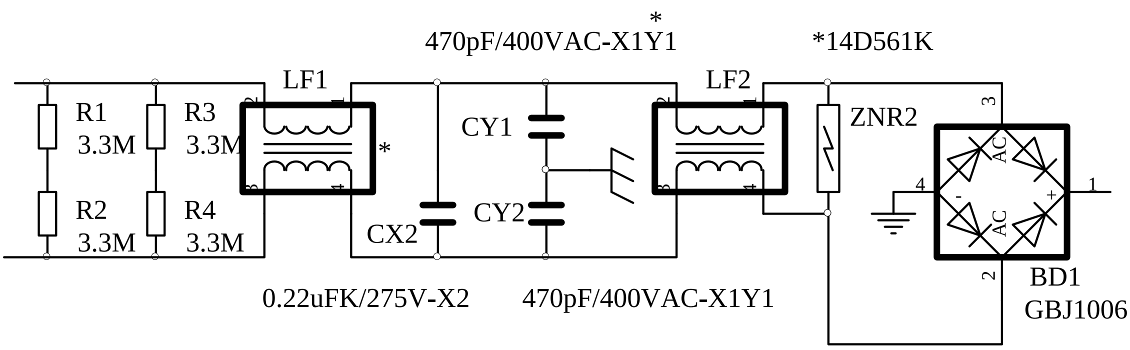

Fig.2. EMI suppression filter

3.3 Active power factor correction circuit

Power factor is the ratio of active power to apparent power [7]. In the electronic devices containing AC/DC converter, the power supply for the DC/DC converter or DC/AC converter is usually the DC voltage obtained by rectifying AC mains power and large-capacitance filtering. The filter capacitor makes the output voltage smooth and the output current a spike pulse. If there is no filter circuit after the rectifier circuit but only the resistive load, the input current will be the sine wave having the same phase as the voltage of the power supply and a power factor of 1. The basic principle of the active power factor correction circuit is to isolate the rectifier from the filter capacitor, thus turning the capacitive load into resistive load in the rectifier circuit.

Power factor correction falls into two categories, active and inactive [8]. Active power factor correction (APFC) circuit has an active power controller connected in series between the rectifier and the output capacitor. As a result, the input current and input voltage of AC/DC converter will be sine waves having the same frequency and the same phase. The input current is forced to go with the input voltage, thus realizing unity power factor. APFC can improve the power factor and overall efficiency of the switching power supply and prevent harmonic pollution of the grid. We use analog integrated circuit L6562 for APFC.

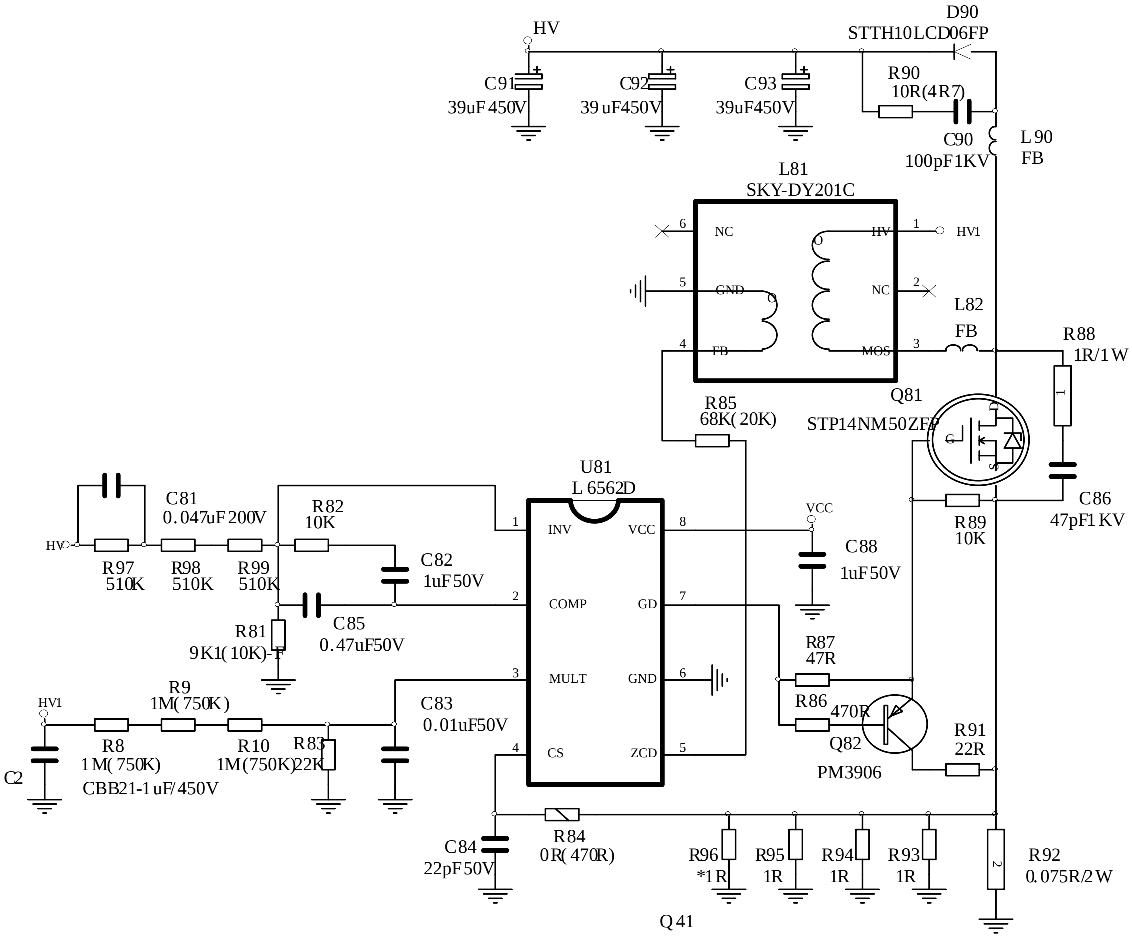

Fig.3. L6562 circuit

As shown in Fig. 3, the output voltage HV of the APFC passes through the sampling resistor and then into the inverting input of the error amplifier through the pin INV. The reference voltage of 2.5V is input to the non-inverting terminal. After amplification, it is input into the multiplier M2. The AC voltage which has passed through the full-bridge rectifier is then sampled by the voltage divider of the sampling resistor. It is input into multiplier M1 through the MULT pin. The output voltage of the multiplier is proportional to the product of M1 and M2. The series connected source resistor of power MOSFET is responsible for the sampling of the peak current of drain voltage-increasing inductor L. It is input into the error amplifier via CS pin and compared with the output voltage of the multiplier. When the voltage of the CS pin reaches the threshold value, that is, when the current reaches the peak in L, the PWM comparator will stop driving the gate of MOSFET.

3.4 Flyback typology

Flyback circuit refers to the following condition. When the switching tube is conducted, driving the primary side of the pulse transformer, the secondary side of the transformer does not supply power to the load [9]. This is the alternating conduction and disconnection of the primary and secondary side. But due to leakage inductance of the transformer, the primary side will have voltage spikes, causing the breakdown of the switching device. Therefore, it is necessary to install the RCD clamp circuit. Single-terminal flyback driver circuit can satisfy the requirement as a small-power high-frequency switching power supply. Furthermore, since the transformer in the flyback typology switching power supply plays the dual roles of inductor and transformer, only the filter capacitor needs to be selected, but not the filter inductor. The circuit structure is simple. The typical isolated flyback driver circuit is shown in Fig. 4.

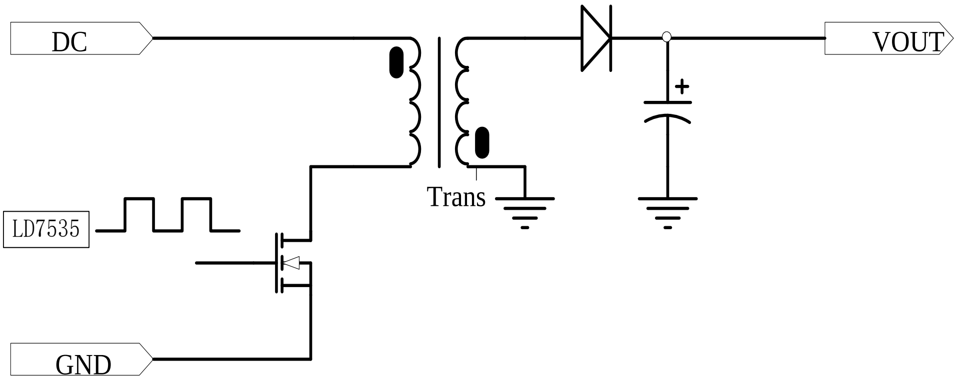

Fig.4. Isolated flyback driver circuit

LD7535, the pulse-width modulator, outputs the PWM signal to control the conduction and disconnection of MOSFET. The working frequency is 50-130KHz and it is adjusted by grounding a resistor through pin 3. The working frequency is 100K, and the corresponding switching frequency is 65KHZ. When MOSFET is conducted, it stores energy in the primary coils of the transformer. The diode connected to the secondary side of the transformer is in reverse biased state and so the diode is disconnected. No current flows through the secondary circuit of the transformer, and therefore no energy is supplied to the load. When MOSFET is disconnected, the voltage polarity in the secondary coils of the transformer is reversed, thus conducting the diode and charging the output capacitor. In the meantime, the current flows through the load.

3.5 Half-bridge resonant typology

Resonant power supply represents the new trend of switching power supply. The sine wave is generated by the resonant circuit, and the switching tube is turned on and off during zero crossing of the sine wave. Therefore, the MOS tube of the half-bridge circuit is alternately conducted and disconnected. By regulating the switching frequency, the average output voltage on the secondary side of the transformer can be changed. The half-bridge resonant typology combined with APFC can achieve a power factor above 0.95, thus greatly inhibiting harmonic pollution of the grid [10].

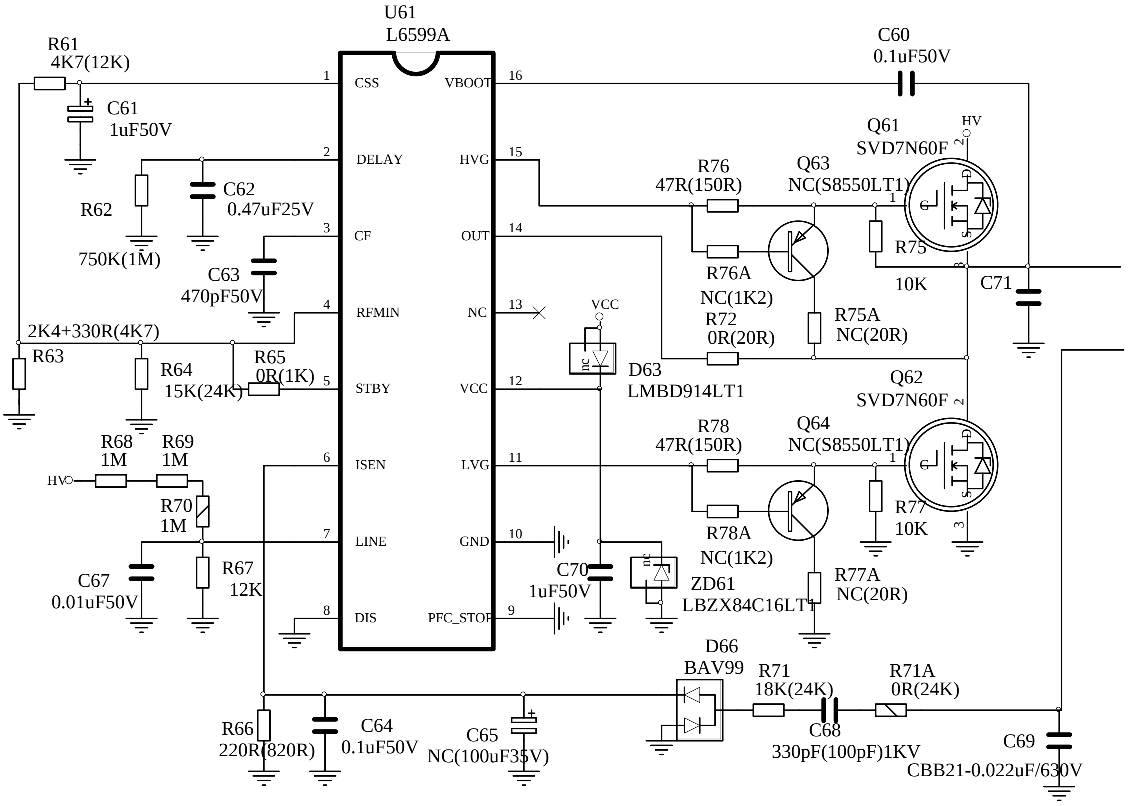

Fig.5. L6599 circuit

L6599 is a double-ended controller specific for half-bridge resonant typology, outputting signals with phase difference of 180° and 50% duty cycle. Unlike PWM controller, energy is transmitted by adjusting the duty cycle. For the half-bridge resonant typology, the duty cycle is fixed, so the energy transmission is controlled by the switching frequency. The output voltage is controlled by the working frequency. As shown in Fig. 5, a resistor RF min is grounded via pin 4 for configuring the lowest oscillation frequency. Resistor RF max is grounded via pin 4. Photo-coupled grounding is controlled by the feedback circuit and the oscillation frequency of the controller is adjusted along with the output voltage. RF max is for configuring the highest working frequency.

3.6 Output rectifier and filter circuit

The output voltage of the switching power supply needs to be rectified and filtered. Schottky rectifier diode depends on the working of most charge carriers and can be conducted and disconnected easily. It has a small positive voltage drop, which decreases with higher temperature. Therefore, the loss arising from conduction is reduced. The following principles should be adhered to when choosing the parameters of the output rectifier tube. The rated current should be at least three times that of the maximum output current of the circuit. The working peak reverse voltage should be higher than the minimum permissible voltage.

Output filter converts the AC square waves into DC current. As shown in Fig. 6, the rectified waveform is directly input into the filter and smoothed into DC waveform by high-capacitance filtering. L51 and C55 make up the post-filter that smooths the waveform and reduces ripple.

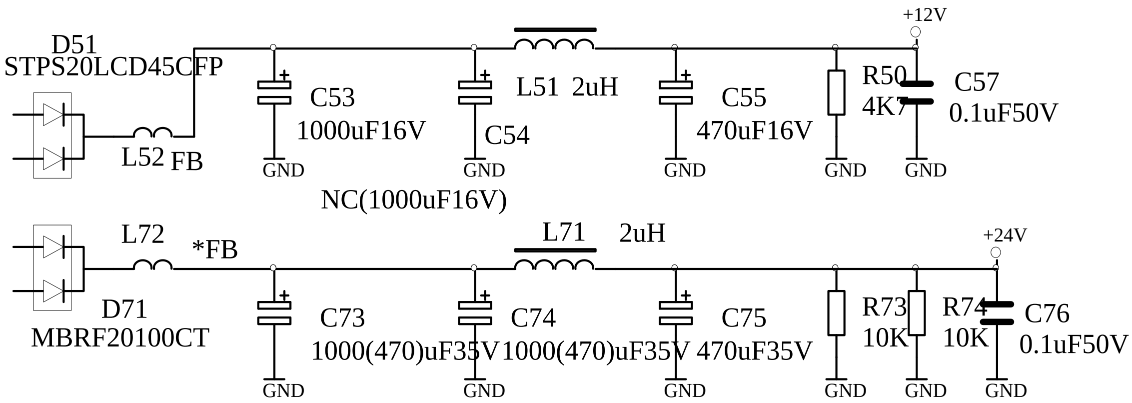

Fig.6. Output rectifier and filter circuit

3.7 Feedback voltage stabilizing circuit

Closed-loop feedback is used to stabilize the output voltage. Optical coupler is used for input sampling, signal feedback and driving output. The feedback circuit is designed as shown in Fig. 7. TL413 is a precision voltage stabilizer that stabilizes the voltage at pin 2 of the optical coupler PC817C at 2.5V. When the output voltage of 24V increases, the voltage of pin 2 remains constant, while the voltage of pin 1 increases. As a consequence, the light emitting device is conducted and gives off light. The light receiver is also conducted and the voltage of pin 4 decreases. On the contrary, when the output voltage of 24V decreases, the light receiver is disconnected and the voltage of pin 4 increases. The voltage level of pin 4 of PC817C is feedback to the control chip. By regulating the duty cycle, the voltage is stabilized.

R54 and R56 are the output sampling resistors. They divide the output voltage by controlling the shunt from the cathode to the anode via the REF terminal of TL431. This current directly drives the light emission of the optical coupler. When the output voltage increases, Vref increases as well, leading to increased current flowing through TL431. As a result, the light emitted by the optical coupler becomes stronger and the feedback voltage at the light sensing terminal increases as well. The PWM control chip, upon receiving this feedback voltage, will change the switching time of MOSFET and the output voltage will drop.

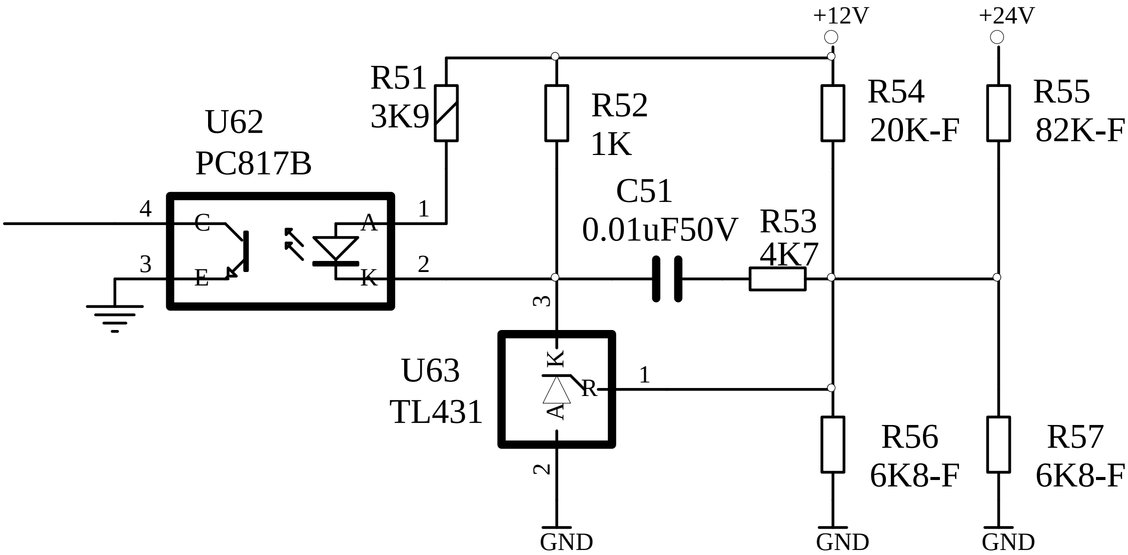

Fig.7. Feedback circuit

4. The Main Hardware Circuit

The circuit diagram consists of three parts, namely, input circuit and APFC module, flyback typology, half-bridge resonant typology and PCB design. For each part, the circuit diagrams are shown in Fig. 8, Fig. 9, Fig. 10, and Fig. 11, respectively.

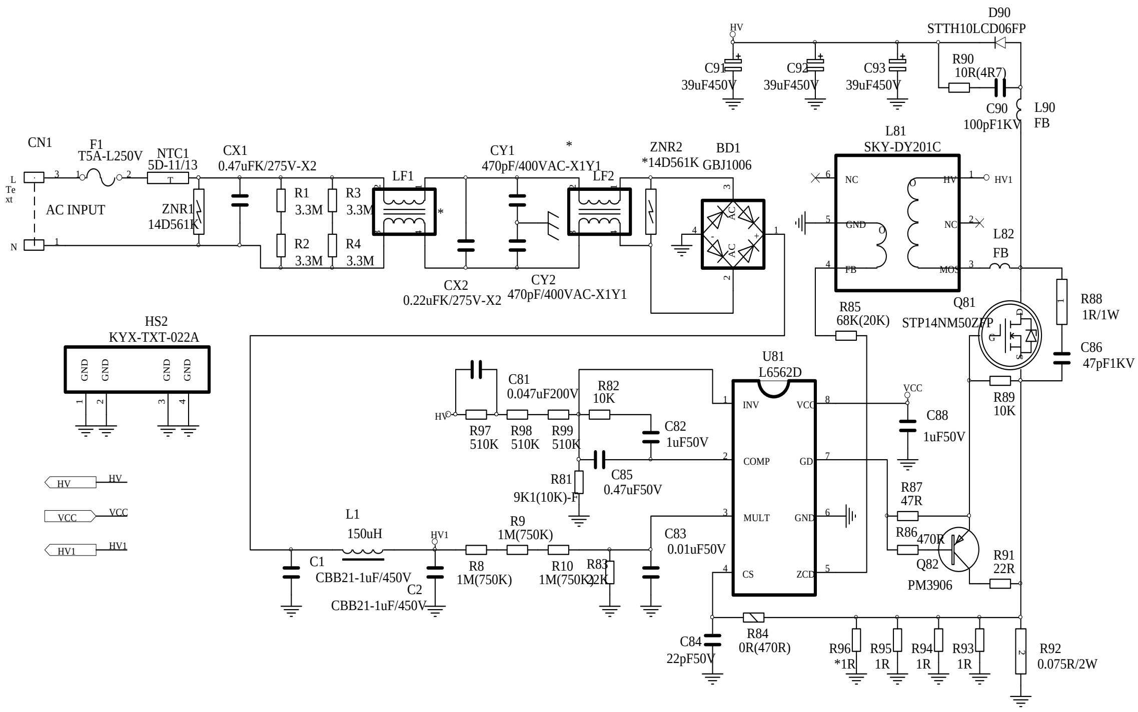

Fig.8. Input circuit and APFC module

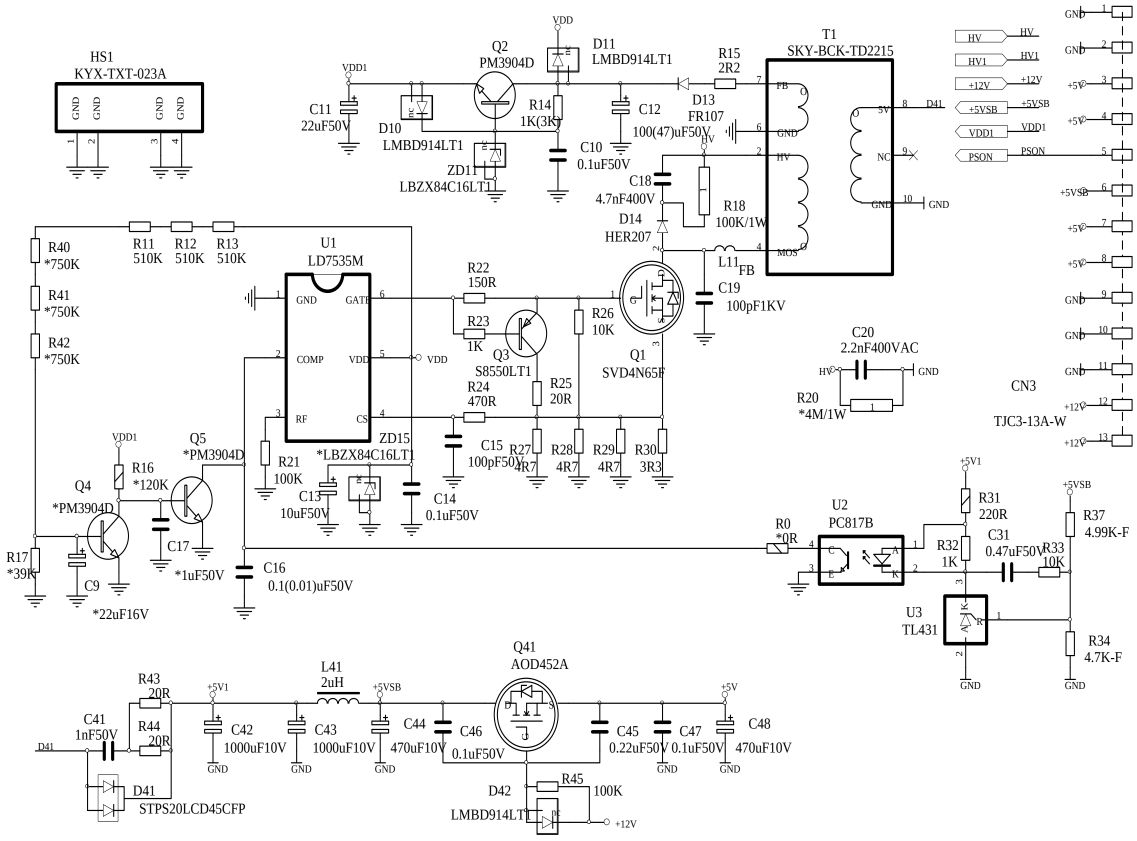

Fig.9. Flyback typology

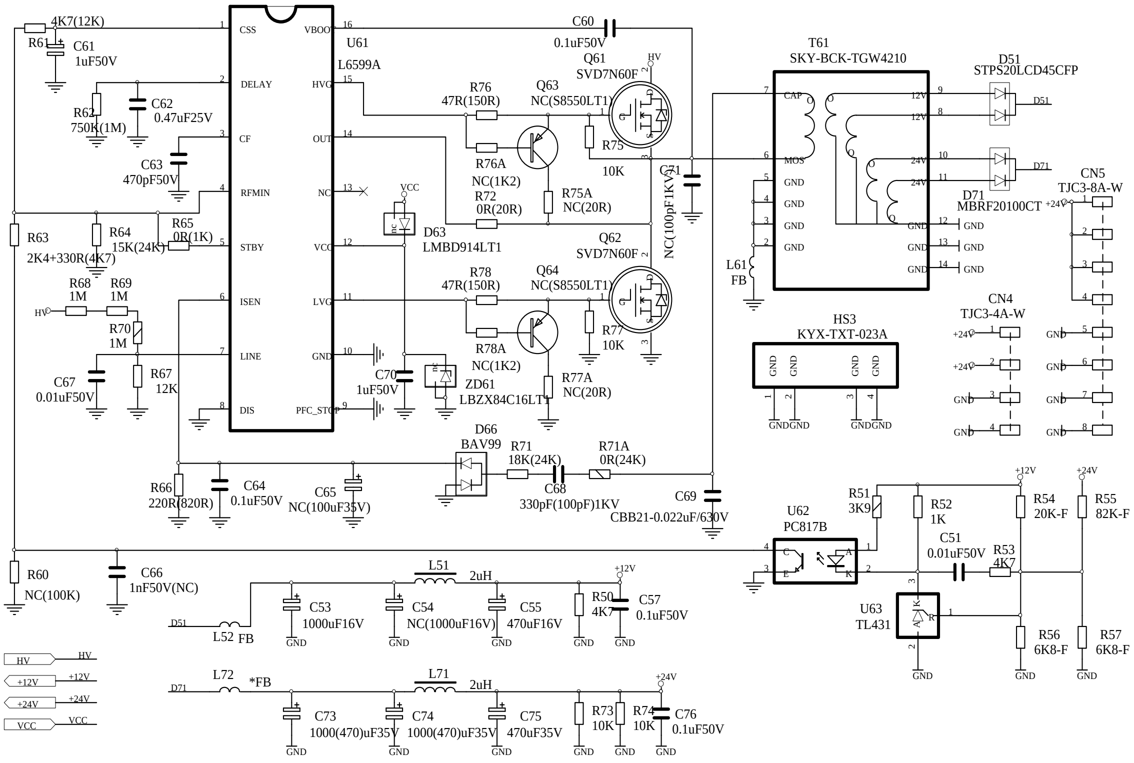

Fig.10. Half-bridge resonant typology

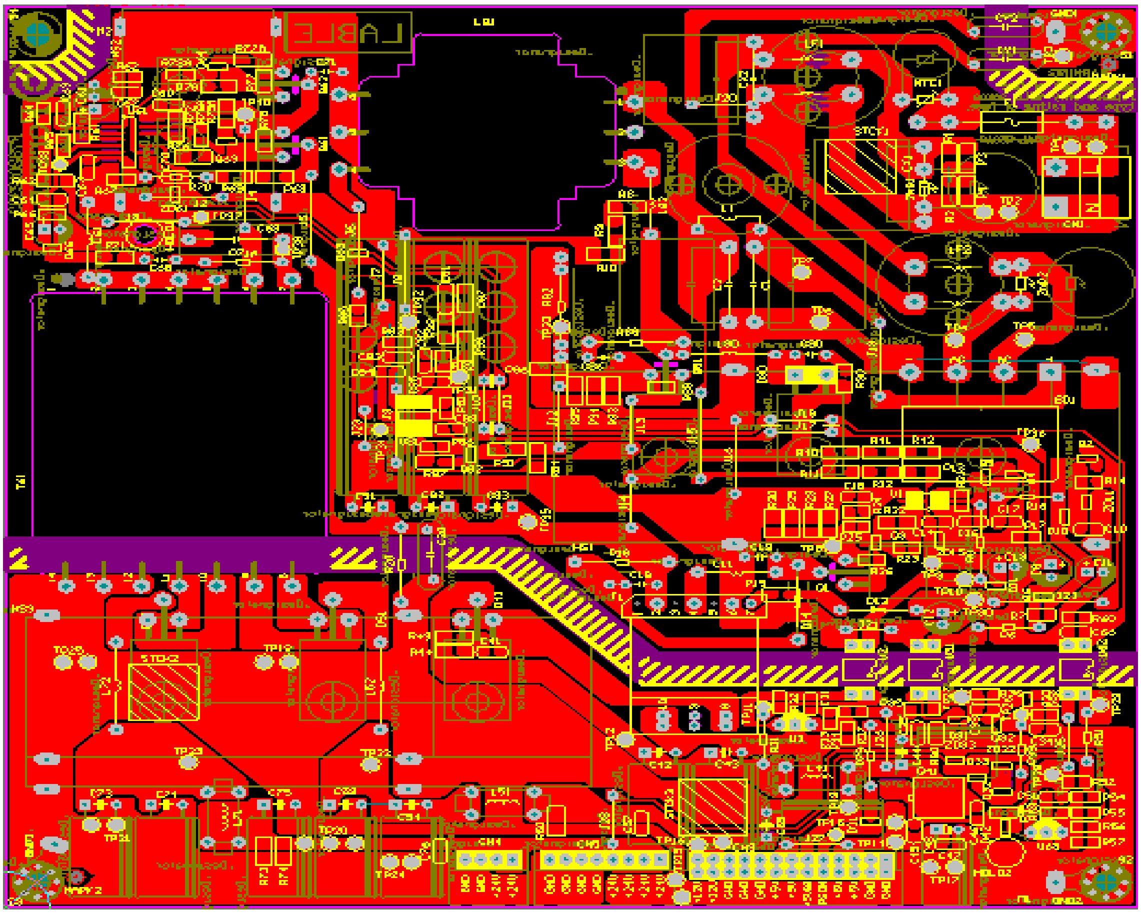

Fig.11. PCB design

5. Experiment and discussion

The performance test of switching power supply is important for performance evaluation. The test items include overall efficiency, power factor, cross loading, ripple and noise, output voltage overshoot and temperature rise. Here the equipment tested is composed of 3KW AC auto transformer, CHROMA 650 electronic load, TDS3032B oscilloscope and P6021 current probe.

5.1 Overall efficiency and power factor

Overall efficiency and power factor are tested to see if they satisfy the requirement. Under AC220V/50HZ, the overall efficiency should be no less than 85% and the power factor no less than 0.92 when the overall power of the power supply is smaller than 1500W.

Tab. 3 Test result of overall efficiency and power factor of the power supply

	Full Load（%）		80% Load（%）		Half Load（%）	
	PF	Efficiency	PF	Efficiency	PF	Efficiency
90V	99.7	86.01	99.7	86.90	99.6	86.87
120V	99.5	88.24	99.6	88.45	99.3	88.10
160V	99.5	89.22	99.2	89.40	98.3	88.68
220V	98.3	89.98	97.7	89.99	96.8	89.03
264V	96.7	90.16	95.2	90.21	94.3	89.03

As shown in Tab. 3, the minimum efficiency is 86.01% and the maximum is 90.21% under different loads; the minimum power factor is 94.3% and the maximum power factor is 99.7%. The performance is excellent and satisfies the requirement.

5.2 Cross loading test

Cross loading test is to evaluate the voltage regulation capacity under unbalanced load. It is checked whether the output voltage varies with the load and whether the variation range of the output voltage exceeds the specified value.

As shown in Tab. 4, when output voltage is 5V and 12V (heavy load) and the output voltage is 24V (light load), the actual output voltage is 24.64V under the load of 24V. Thus, under unbalanced load with multi-route output, the output voltage fluctuates greatly. We use the TL431 precision shunt regulator for feedback regulation and achieve satisfactory effect.

5.3 Ripple and Noise

Ripple and noise are tested as well. The high-frequency and low-frequency ripple and noise are displayed on the oscilloscope. For this test, a 47uF capacity together with a 0.1uF capacitor is connected to the voltage probe of the oscilloscope. The test is performed at broadband 20MHz AC mode. Under input voltage of 240V and full load condition, the ripple and noise of the three output routes are shown as follow.

Tab. 4 Result of cross loading test

5V	12V	24V	5V	12V	24V
0.1A	0.3A	0.2A	5.16V	11.97V	24.22V
0.1A	0.3A	4.0A	5.16V	12.04V	23.91V
0.1A	2.0A	0.2A	5.15V	11.88V	24.63V
3.0A	0.3A	0.2A	5.12V	11.97V	24.24V
0.1A	2.0A	4.0A	5.15V	11.95V	24.30V
3.0A	0.3A	4.0A	5.12V	12.04V	23.93V
3.0A	2.0A	0.2A	5.11V	11.88V	24.64V
3.0A	2.0A	4.0A	5.11V	11.95V	24.32V

Tab. 5 Test result of ripple and noise

	Load	Ripple	Ripple and Noise
5V	3A	09.6mv	15.6mv
12V	2A	37.8mv	52.8mv
24V	4A	117.0mv	181.0mv

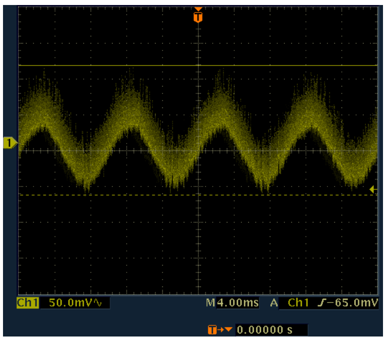

Fig. 12 5 V ripple

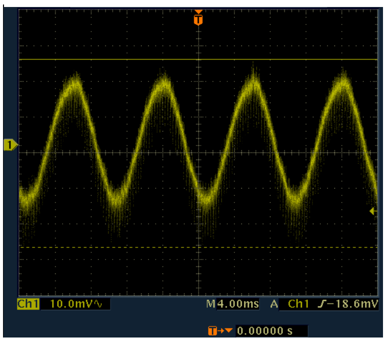

Fig. 13 12V ripple

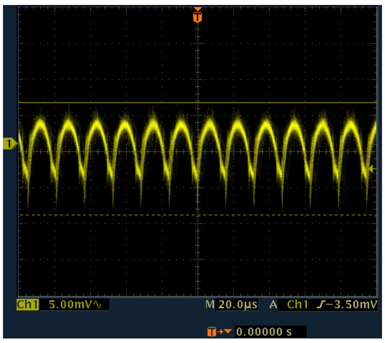

Fig. 14 24V ripple

Ripple is a component synchronized with the input frequency and switching frequency between the output terminals. Expressed as the peak-to-peak value, ripple is usually below 0.5%

of the output voltage. Noise is a high-frequency component between the output terminals and its value is about 1% of the output voltage. Ripple noise is the synthesis of the two and generally below 2% of the output voltage. As shown in Tab. 5, the ripple and noise in all three output routes satisfy the requirement.

5.4 Output voltage overshoot and time-to-climb

Output voltage overshoot and time-to-climb are the peak values causing the changes of DC voltage when the power supply is turned on or off. When the power supply is turned on, the voltage overshoot and time-to-climb are recorded with the oscilloscope. Under the input voltage of 220V and full load conditions, the output voltage overshoot and time-to-climb are measured as follows.

Tab. 6 Output voltage overshoot and time-to-climb

Output Voltage	Load Current	Overshoot	Rise Time
+5V	MAX	0.000%	01.6ms
+12V	MAX	3.840%	06.8ms
+24V	MAX	2.789%	05.6ms

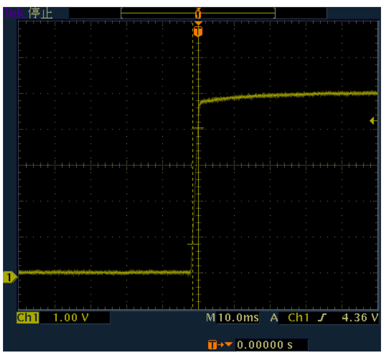

Fig. 15 5V overshoot

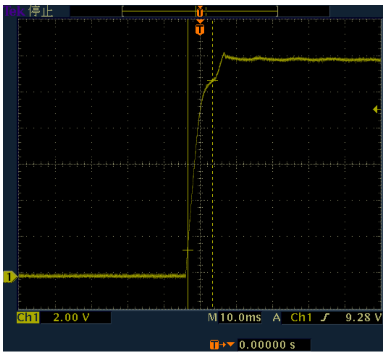

Fig. 16 12V overshoot

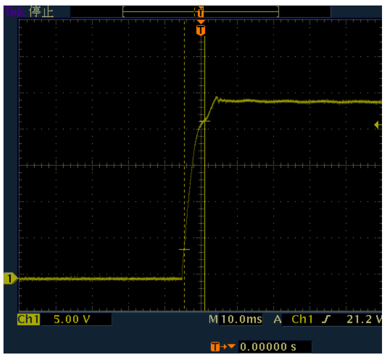

Fig. 17 24V overshoot

According to relevant standards, the overshoot of the power supply should not exceed ±10% of the output voltage. In Tab. 6, the maximum overshoot is 3.84%, which satisfies the requirement.

Conclusion

Switching power supply is now considered a substitute for linear power supply due to its various advantages. We design a novel type of switching power supply with three outputs (5V, 12V, 24V) by combining flyback circuit and half-bridge resonant typology and using TL431 circuit and PC817 optical coupler. The experiment shows that this switching power supply has good voltage stabilizing performance, with small ripple, high power factor, high voltage regulation and high load regulation. Compared with ordinary switching power supply, the proposed power supply has higher precision of output voltage, higher power factor, smaller ripple, lower load regulation and voltage regulation. Moreover, the power is larger and the load-carrying capacity is improved.

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