Design of A Novel High Precise Direct Current Negative High Voltage Power Supply

ZHAO YANLEI, JIANG ZHIHAI, LIU WEI
School of Electrical & Electronic Engineering
Shandong University of Technology
No. 12 Zhangzhou Road, Zhangdian District, Zibo, Shandong Province
CHINA

Abstract: - This paper introduces a high precise direct current (DC) negative high voltage power supply. The supply's output voltage is 25kV and its maximal output current is 100mA. The power supply uses BOOST converter for power factor correction and voltage regulation. It converts DC to high frequency (HF) alternating current (AC) square wave with phase-shifted full bridge. The voltage of the AC square wave is boosted by HF transformer, then the HF high voltage AC square wave is double rectified to DC high voltage output. The HF high voltage transformer, which is designed and manufactured with special material and technique, solves several technical difficulties including influence of distributing parameters and insulation, and meets demands of high frequency, high voltage and high power. The experimental result shows the power supply has high input power factor, stable output voltage and small ripple.

Key-Words: - DC high voltage power factor correction ZVS phase-shifted control

1 Introduction

The high voltage power supply, including positive voltage source and negative one, is wildly used in various fields such as scientific research, industry and medical treatment. Of these fields, to satisfy usage demands, the high voltage power supply should has high precision and low ripple.

At present, the rapid development of power electronics prompts the trends of high voltage power supply to high switch frequency. However, the technique in the HF high voltage power supply whose output power is more than 1 kW isn't mature yet. There are three main problems[1~5]: (1) the rectifier in the suppuly is composed of dioded or of thyristors, which leads to input power factor is low; (2) the switching frequency of the converter in the suppuly is not high enough, which leads to the output voltage ripple is high; (3) it's difficult to deal with the insulation, parasitical inductance and distributed capacitor of the high voltage HF transformer, to solve these problems, the transformer is generally dipped in insulative oil, but which leads to large size and the inconvenience of installation, transportation and placement.

According to actual application demand, the paper researches on and develops a high precise negative high voltage power supply used for industrial analysis, whose output voltage is 25kV. The steady output current of the power supply is about 60 mA and the maximal 100 mA.

The paper uses BOOST converter for power factor correction and voltage regulation, which improves input power factor and reduces output ripple of the power supply. And the paper adopts special material and design method, which solves the problems of insulation and parasitical parameters of transformer under high voltage and high frequency.

2 The topology and operation principles of the high voltage source

Shown as Fig. 1, the high voltage power supply is composed of rectifier, primary stabilizing and power factor correction (PFC) circuit, zero voltage switching (ZVS) phase-shift full-bridge inverter, HF high voltage transformer and double-voltage rectifier.

The first rectifier, using full-bridge uncontrolled rectifier, changes the grid voltage to DC pulsant one. The primary stabilizing and power factor correction (PFC) circuit is realized by a BOOST converter, which has two functions: (1) to make input current i_s track input voltage u_s by current feedback, which guarantees input power factor of the power supply is close to 1; (2) to adjust the output voltage U_d of PFC circuit, which guarantees the output voltage of the power supply is stable. To reduce switching losses and to diminish voltage ripple, the inverter adopt ZVS phase-shift full-bridge circuit, which converts smooth DC voltage to AC square wave with high frequency. The HF high voltage transformer is the key of the power supply, which boosts AC square wave to scheduled high voltage. Double-voltage rectifier, including rectifier circuit and filter one, changes the HF high voltage AC square wave to smooth DC negative high voltage.

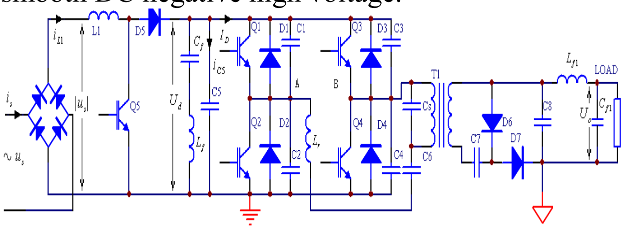

Fig. 1 Structure diagram of the main circuit

In the power supply, the duty cycle of the switches of the phase-shift full-bridge inverter is constant and equal to 0.95, hence the adjustment of output voltage is realized only relying on primary stabilizing and PFC circuit.

The switch Q5 in BOOST converter is realized by IGBT (Toshiba MG50Q1ZS50) and the switches Q1~Q4 are realized by IGBTs (Mitsubishi CM50DU-24F). The control structure of the whole power supply is illustrated as Fig. 2.

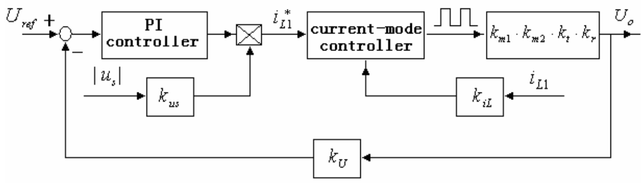

Fig. 2 Structure of the control system

k_{us} --sampling gain of pulsant DC voltage $|u_s|$; k_{iL} --sampling gain of incductance current i_{L1}; k_U -- sampling gain of output voltage U_o; k_{m1} --the gain of BOOSTconverter ; k_{m2} -- the gain of inverter ; k_t --the transforming ratio of transformer; k_r -- the gain of mulitple-voltage rectifier ; U_{ref} --the reference value of output voltage; i_{L1}^* --the reference value of current controller

3 The key techniques of the high voltage source

3.1 The primary stabling and PFC circuit[3~6]

To make the input current track input voltage, BOOST converter runs in current-control mode. The error between reference voltage U_{ref} and feedback of output voltage U_o is adjusted by PI controller, whose output is multiplied by the measure signal of pulsant DC voltage $|u_s|$ and gains the reference current i^*_{L1}. In the control of the power supply, the switching frequency is invariable. When the current i_{L1} of inductor L1 increases to i^*_{L1}, the switch Q5 is switched off for a while; when the switching period is over, Q5 is switched on again. And the process above mentioned is circulated repeatedly, which not only realizes power factor correction, but also guarantees the stabilization of output voltage. The paper selects the integral control IC--UC3854, which can realize these functions expediently. Under the condition that the switching frequency is invariable, the duty cycle D changes when input voltage changes and there is the below relationship:

$$|u_s|/U_d = 1 - D \quad (1)$$

in the design, U_d is selected as 350V.

Suppose BOOST converter runs in ideal state, the input power is equal to the transient power, by which the ripple voltage of filter capacitor C5 can be deduced:

$$\Delta U_d(t) \approx \frac{1}{C_5}\int i_{C5}dt = -\frac{I_d}{2\omega C_5}\sin 2\omega t \quad (2)$$

in formula (2), ω is the frequency of the grid voltage; I_d is the average current flowing to the back circuit.

Under the circumstance that the load of the power supply is maximal, $I_d = \frac{25kV \times 100mA}{350V} \approx 7A$.

According to formula (2) and ripple restricting condition-- ΔU_d =2% U_d, the filter capacitor C5 can gained by calculation: $C5 = 3185uF$, and is selected as $3000uF$.

In addition, a LC composed of L_f and C_f , whose resonant frequency is 2ω , can effectively eliminates low order harmonics.

3.2 The HF high voltage transformer

The HF high voltage transformer is the core and the difficult point in the whole high voltage power supply, under the condition of high voltage and high frequency, whose parasite parameters and distributed ones directly influence the performance of the high voltage power supply. In the design process, three factors are considered: (1) the leakage inductance of the transformer. The leakage inductance at high frequency shall restrict the output power of the power supply, at the same time, the leakage inductance, being as resonant inductor of phase-shift full-bridge inverter, should guarantees the switches in the inverter switch under zero voltage. (2) the distributed capacitor of the transformer. The distributed capacitor at high frequency shall reduce power factor and increase empty-load current. (3) the insulation of the transformer. The insulations between low voltage side and high voltage side, between different windings, between layers are should considered.

In the design process, transforming ratio of the transformer should be determined firstly. Considering the loss of duty cycle of transformer's second side under ZVS phase-shift, the duty cycle of transformer's second side is determined as 0.85, so the voltage of transformer's second side is:

$$U_{\sec} = \frac{U_o/2 + \Delta U}{D_{\sec}} = \frac{25kV/2 + 1\% \cdot 25kV}{0.85} = 15kV \quad (3)$$

in formula (3), U_o is output voltage; ΔU is voltage drop of the filer inductance. So the transforming ratio of transformer is:

$$n = \frac{U_{\sec}}{U_d} = \frac{15kV}{350V} \approx 42.86 \quad (4)$$

n is selected as 43.

The paper selects ferrite magnetic core (UF96), whose effective area A_e conducting magnetism is $9cm^2$ and saturation magnetic induction intensity $B_S = 4700GS$. To avoid magnetic saturation, the maximal single direction magnetic induction intensity is selected as:

$$B_m = \frac{1}{2} B_S = 2350GS = 0.235T \quad (5)$$

switching frequency of the inverter $f_s = 40kHz$, the winding turns of transformer's primary side is:

$$N_1 = \frac{U_d \cdot D}{2f_s \cdot A_e \cdot B_m} \times 10^4 = \frac{350 \times 0.9}{2 \times 40000 \times 9 \times 0.235} \times 10^4 \approx 19$$

the winding turns of transformer's second side is: $N_2 = n \cdot N_1 = 43 \times 19 = 817$.

To solve the problems aroused by parasite induction, distributed capacitor and insulation in transformer, some measures are taken with regard to the structure and the material of the transformer: (1) the low voltage windings and the high voltage ones are isolated by using two frameworks of different dimension, which are coupled inside and outside, respectively. (2) the high voltage winding framework is made of special material—polytetrafluoro ethylene (F4), which has good insulation performance. (3) there are 21 grooves in the surface of the high voltage winding framework, and the bordered grooves are isolated by F4 with appropriate thickness. The winding is divided averagely and there are 39 turns of windings in each groove which is divided 4 layers, inserting the polyester film between layer and layer. As a result, the voltagea groove bears is only about 720V, and there is a voltage about 180V between layer and layer in each groove. (4) to diminish the voltage between layer and layer and reduce distributed capacitor, the high voltage windings is divided into many subsection, then is coiled. (5) the surface of the transformer is sealed by epoxy colophony and the windings is immersed by paint in the vacuum condition. (6) the high voltage winding is covered by a F4 cover, which prevents air discharge.

3.3 ZVS Phase-shift full-bridge inverter

As shown in Fig. 1, C1~C4 are output junction capacitors of the switches Q1~Q4, and L_r is resonant inductor, C6 is the capacitor blocking DC and used to prevent transformer's DC magnetization. C_s is mainly used to absorb the peak voltage of transformer. Accorrding to [6], the leading arm can easily realize zero voltage switching (ZVS), while the lagging arm is difficlut to realize ZVS. Take Q3 for example, to achieve ZVS, the following formula must be meet:

$$\frac{1}{2} L_r I_P^{\ 2} > C_3 U_d^{\ 2} \quad (6)$$

in which, I_p is the current of tranformer primary side when Q3 is switched off.

In the design process, it's destined that the lagging arm realizes ZVS when output current is equate to or more than 30mA. At this point the current equivalent to transformer primary side is: $I_P \approx 2 \times 43 \times 30mA \approx 2.6A$. Known from manual data of IGBT CM50DU-24F that its typical junction capacitance value is 0.85nF, According formula (6), in order to ensure that lagging armcan achieve ZVS, $L_r > 30.8uH$. The transformer leakage inductance is about $29uH$ in the design of the paper, so it can work as a resonant inductor. In the condition of one third of the maximum load, lagging arm can realize ZVS. Hence, in this power supply design , resonant inductor is also transformer leakage inductance in ZVS phase-shift full-birdge inverter.

The loss of duty cycle of transformer's second side is decided by formula:

$$D_{loss} = L_r \frac{2n \cdot \{(I_o + \Delta I/2) - [-(I_o - \Delta I/2)]\}}{U_d \cdot \frac{T_S}{2}} = \frac{8nL_r I_o f_S}{U_d} \quad (7)$$

when output current I_o is 100mA, substitutes the actural values of the remaining variables into formula (7), it's can be gained that the largest duty cycle loss is 0.114. When the inverter maintains constant duty cycle of 0.95, in such a loss of duty cycle, the output voltage U_o can be adjusted by primary stabling and PFC circuit to ensure its stability. The inverter is controlled by IC--UC3875.

3.4 The double-voltage rectifier and sampling of output voltage

The main parameters of the double-voltage rectifier are as below: maximum input voltage is 30kV; maximum input current is 500mA; maximum output voltage is 50kV; maximum output current is 200 mA; the ripple coefficient is 1% when the frequency of its input voltage is 10kHz and 0.2% 30kHz; in addition, there are built-in filtering circuit and resistors for voltage sampling. The voltage signal gained by the built-in resistors is sent to a voltage follower, whose output signal is amplified by a linear optocoupler and sent to back signal dealing circuit. The model of operational amplifier used as voltage follower is LF444A, and the model of optocoupler is HCNR200 (Agilent). To prevent voltage sampling resistors from widening arc to generate peak voltage which will damage voltage follower, a TVS (transient voltage suppressor) clamp circuit and a RC filter circuit are installed in the input of voltage follower. Sampling circuit is shown in Fig. 3.

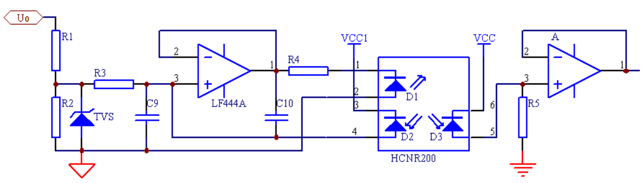

Fig. 3 The circuit of the output voltage sampling

4 The experimental results

The experimental results indicates that: the lagging arm can realize ZVS when the output current of the power supply is equal to or more than 28mA; the input current can track the input voltage well and output voltage has good stability when the load alters in a wide scale. When load current is 85 mA, the input power factor is 0.99 and ripple coefficient of output voltage is below 0.3% (peak-to-peak).

Fig. 4 shows the waveforms of input current and input voltage, and Fig. 5 output voltage and its spectrum.

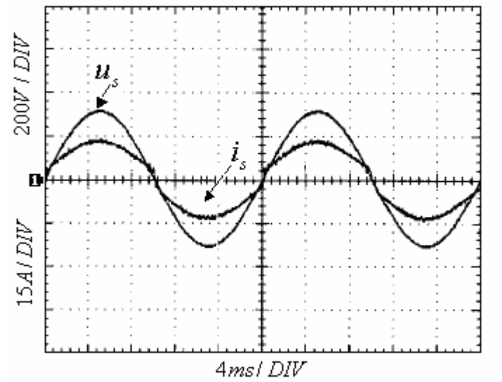

Fig.4 Input voltage and input current

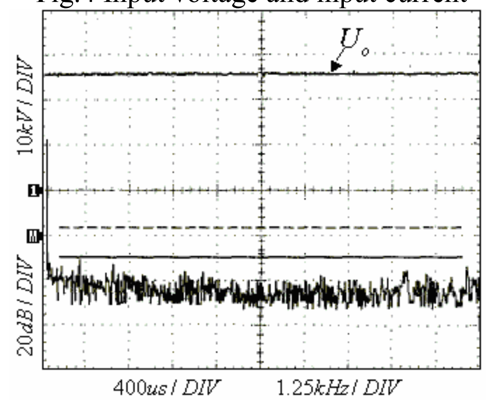

Fig.5 Output voltage and its frequency spectrum

5 Conclusion

The high voltage power supply designed in the paper, using two high frequency converters as well as high voltage high frequency transformer and rectifier, not only diminishes output voltage ripple, but greatly increases the input power factor, so avoids the pollution to the grid in great degree. The transformer designed and manufactured by special material and technique, solves several technical difficulties such as the influence of parasite parameters and insulation, and meets demands of high frequency, high voltage and high power. The experimental result shows the power supply has high input power factor, stable output voltage and small ripple.

References:

[1] Barry C Pollard, Nelms R M. Using the series parallel resonant converter in capacitor charging applications[C]. *The 7th applied power electronics conference and exposition*, Boston, MA, USA, 1992: 245~252

[2] Souda M, Endo F, Yamazaki C, et al. Development of high powers capacitor charging power supply for pulsed power application[C]. *The 12th international pulsed power conf,* Montery, CA, USA, 1999: 1414~1416

[3] Biebach J, Ehrhart P, Muller A, et al. Compact modular power supplies for superconducting inductive storage and for capacitor charging[J]. *IEEE Trans on Magnetics*, 2001, 37(1): 353~357

[4] RIM G H, Jeong I W, Gusev G I. A constant current high voltage capacitor charging power supply for pulsed power application[C]. *IEEE international conference on plasma science*, Las Vegas, 2001: 1248-1286

[5] Ye Hanmin. A novel DC high voltage power supply used for electron beam welder[J]. *High Voltage Technology*, 2003, 29(8): 14

[6] Ruan Xinbo, Yan Yangguang. *PWM DC/DC full-bridge converter soft switching technique* [M]. Beijing: Science press,2001

[7] Chambers D, et al. New high frequency high voltage power supplies for microwave heating applications[C]. *Proceedings of the 29th Microwave power symposium*. Chicago,1994

[8] Marcelo Brunoro,Jose Luiz F.Vzeira . A High-performance ZVS Full-bridge DC-DC 0-50V/0-10A Power Supply with Phase-shift Control[C].*IEEE PESC'99*:495~505