



Development and testing of high precision and stability power supply for high energy photon source

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Abstract

Purpose The high energy photon source (HEPS) is the fourth-generation synchrotron photon source. Compared with the third-generation synchrotron photon source, the brightness is 100–1000 times higher, and the electron emittance of the storage ring is low to the diffraction limit of light. Through physical calculations, it is required that the stability of the storage ring quadrupole magnet power supply be better than 10 ppm, and the accuracy of output current be better than 80 ppm. This high demand for technical parameter poses a challenge to the development of high precision and stability power supplies.

Methods The main circuit topology of the power supply adopts a phase-shifted full bridge soft switching scheme, which avoids interference caused by switching noise and improves power stability and efficiency. The high-precision digital power supply controller based on FPGA improves the sampling speed and control accuracy of the power supply, and the constant temperature control circuit ensures that the output current of the power supply meets the requirements of HEPS for power supply performance.

Results In the batch testing section, a testing facility was built to test the stability, accuracy, repeatability, voltage ripple, and other parameter of high precision and stability power supplies. After a year and a half of testing, the performance tests of 1066 power supplies, including linear accelerators power supplies, booster power supplies, storage rings power supplies, dipole and quadrupole combined power supplies, dipole and quadrupole power supplies, were completed. The results all met and exceeded the design specifications.

Conclusions The HEPS high precision and stability power supply meets the design requirements in terms of current stability, accuracy, repeatability, voltage ripple, and other aspects. The batch test results show that the power supply performance using the full bridge phase shifting soft switching technology combined with high-precision digital controller scheme is excellent, and the power supply consistency is good, providing a guarantee for the successful operation of HEPS in the future.

Keywords Current source · Full bridge phase shifting · Digital control · High stability · Batch testing

Introduction

Based on the power supply parameters, two power supply topologies were designed, with a total of 1066 power supplies. The power control adopts a self-developed digital power control module and combines it with an analog control chip to achieve full bridge phase shifting soft switching control. The controller adopts a constant temperature control

circuit, effectively reducing current fluctuations caused by temperature changes. In terms of power structure, a 4U high case is selected as the main structure of the power supply, and a 19-inch rack is selected. To meet the requirements of batch testing, a batch testing facility has been established, which can simultaneously measure the stability of 25 power supplies, calibrate the coefficients of all power supplies, and complete repeatability testing and ripple testing. Finally, a comprehensive test was conducted on 1066 power supplies and statistics were conducted [1].

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Main power circuit

The output current of the dipole and quadrupole combined power supplies, dipole and quadrupole power supplies is both unidirectional, and the output power of the power supply ranges from a few kilowatts to more than ten kilowatts. Therefore, adopting a full bridge topology can meet the requirements of high-power power supplies. In order to reduce the switching stress of the switch devices, reduce switching noise, and improve power efficiency, a phase shifting soft switch working mode is adopted. The output adopts a full-wave rectification circuit, and the filtering adopts an LC filter. Figure 1 shows power supply main circuit topology [2].

The internal structure of the power supply mainly adopts two designs. The 'tiled' design with IGBT acts as the main switching device and the 'modular' design with MOSFET as the main switching device [3]. The 'tiled' design has good heat dissipation, high utilization of internal space in the power supply, and is easy to maintain. The "modular" design has a compact structure, mainly consisting of PCB assembly, and the components are basically surface mounted, with high integration and suitable for manufacture. Among all high precision and stability power supplies, power above 10 kW adopts a "tiled" design, with a total of 202 units [4]. The power supply with a large number and low power adopts a "modular" design, with a total of 864 units. The two structural designs are shown in Fig. 2.

Power control scheme

The power control adopts a combination of digital control and analog control. In terms of loop control, a dual closed-loop control method of current and voltage is adopted [5]. The current outer loop is given and fed back by a digital power controller based on FPGA. The direct current-current transducer (DCCT) converts the output current in a ratio of 1000:1 and converts it into a voltage through a high-precision, low-temperature drift I/V conversion resistor. An 18-bit high-precision, high-speed AD chip is used for current acquisition. The calculation results of the outer current loop are accurately and quickly transferred to the voltage inner loop through high-precision DA. The voltage inner loop uses an analog chip UC3875 to achieve the control of full bridge phase shifting soft switching and the generation of PWM driving pulses. The control of analog chips increases the speed of the voltage loop and suppresses output voltage ripple. Figure 3 shows the power control block diagram.

The stability requirement of HEPS high precision and stability power supply is better than 10 ppm, and only relying on power filtering is difficult to meet the requirements. And the impact of temperature changes on ADC cannot be ignored and is a key factor. The analog-to-digital converter ADS8382 used by the controller is an 18 bit, fully differential bipolar ADC with a maximum sampling rate of 600 kHz. Every 1 °C change in external temperature will cause a

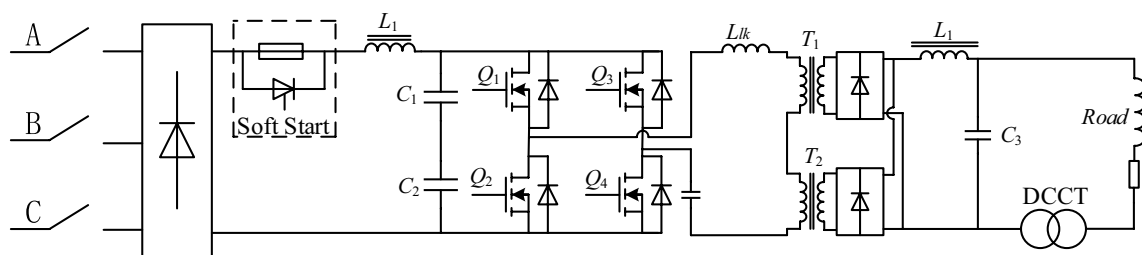
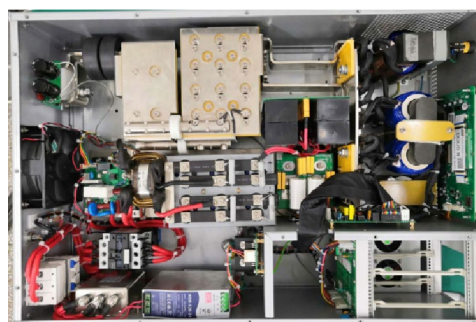
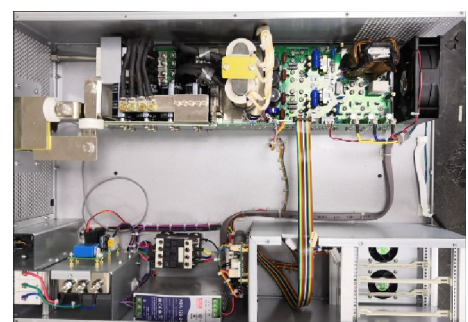


Fig. 1 Power supply main circuit topology

Fig. 2 Internal structure of power supply



a. "Tiled" design



b. "Modular" design

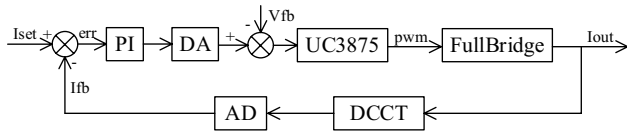


Fig. 3 Power control block diagram

voltage drift of 25 ppm in the internal reference source, which will cause significant changes in the AD sampling results and directly affect current stability. Therefore, the constant temperature control of ADC is crucial. In the design, a constant temperature control circuit is used to control the sampling module at 45 °C, with a control accuracy of 0.1 °C, minimizing the impact of ADC temperature drift on power supply performance. This is the key to achieving a 10 ppm power supply. Figure 4 shows constant temperature control of ADC.

Fig. 4 Constant temperature control of ADC

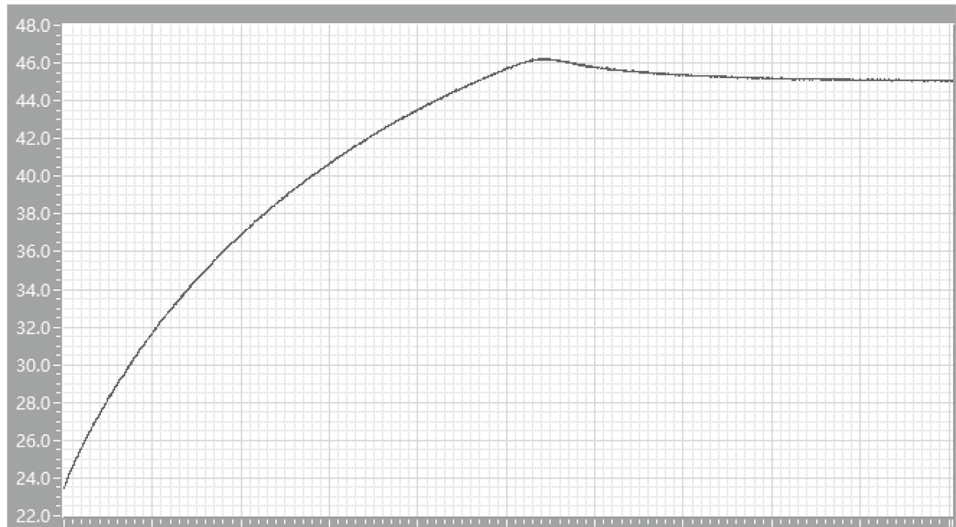


Fig. 5 HEPS high precision and stability power supply



Fig. 6 Batch testing of 25 power supplies

Power supply and rack

The main specifications and quantity of HEPS high precision and stability power supply include 260A/45 V (200 units), 160A/20 V (153 units), 230A/25 V (710 units), and

	开关机设定及回读			状态监测			电流				
	开机	关机	设定回读	h40	h41	h45	设定	设定回读	电流限值	电压	电流偏差
电源ps1	●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	224.9978	225.2529 V	-0.0000 A
电源ps2	●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0017	226.298 V	-0.0000 A
电源ps3	●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0080	224.496 V	0.0000 A
电源ps4	●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0038	225.159 V	0.0000 A
电源ps5	●开	●关	0	●黄	Warning	Remit	225.0000 A	0.3000 A	0.3064 A	0.8973 V	-0.0000 A
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0134	226.795 V	0.0000 A	
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	224.9964	226.443 V	0.0000 A	
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0067	226.218 V	-0.0000 A	
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	224.9959	226.277 V	-0.0000 A	
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0072	240.109 V	0.0000 A	
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0056	227.457 V	-0.0000 A	
●开	●关	0	●绿	Normal	Remit	225.0000 A	225.0000	225.0035	229.953 V	0.0000 A	

Fig. 7 Remote control interface

Table 1 Technical parameter of HEPS high precision and stability power supply

Item	Technical requirement
Stability	10 ppm
Accuracy	80 ppm
Repeatability	50 ppm
Voltage ripple	≤ 300 Hz; $V_{p-p} \leq 100$ mV, $V_{rms} \leq 2$ mV; > 300 Hz: $V_{p-p} \leq 100$ mV, $V_{rms} \leq 15$ mV

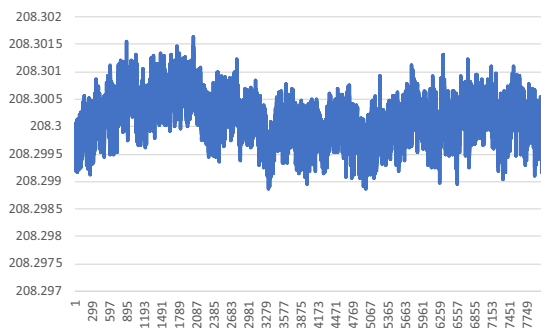
3 other specifications of power supply. The power supply rack adopts a 19-inch-wide, 4U high, and 650-mm-deep iron chassis. The power cooling adopts a water-cooled structure. Use a touch screen for local operation and display.

The power rack is 2000 mm high, 800 mm wide, and 1000 mm deep. According to the location of HEPS magnets and the layout of the power hall, each rack can accommodate 5 power supplies. There is a height of 1U for placing the current sampling chassis. According to the location of the on-site power supply, the power load wire placed in the 8 power supply halls on the first floor of HEPS is led out from the top of the rack, while the power supply placed on the second-floor platform of HEPS is led out from the bottom of the rack. The rack has a main water inlet pipe that provides water distribution for 5 power supplies. Figure 5 shows the appearance of a high precision and stability power supply.

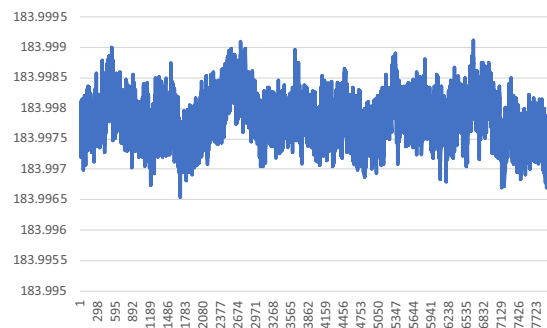
Table 2 Measurement reference calculation formula

	Stability	Accuracy	Repeatability
Formula	$I_{stability} = \left \frac{I - I_{avg}}{I_N} \right _{max}$	$I_{accuracy} = \left \frac{I_{avg} - I_{set}}{I_N} \right _{max}$	$I_{reproducibility} = \left \frac{I_{avg} - \langle I_{avg} \rangle}{\langle I_{avg} \rangle} \right _{max}$

I : current value; I_N : rated current value; I_{avg} : average current value; I_{set} : set current value; I_N : rated current



a. 80% of 260A/45V output



b. 80% of 230A/25V output

Fig. 8 Current stability test

Power batch testing facilities

To meet the batch testing requirements of HEPS power supply, a testing facility has been built for comprehensive testing of power supply performance. These facilities have the ability to simultaneously measure 25 power supplies. The total distribution capacity is 400 kW, which can meet the full power operation of 25 sets of 260A/25 V power supplies simultaneously. We have customized 25 high-power resistance boxes made of Constantan (6J40) and placed them outdoors. Each load circuit is equipped with a standard DCCT sensor and corresponding power supply, as well as high-precision I/V conversion resistors, for various performance tests of the power supply. Using 3 KEITHLEY 7 1/2 digital meters, each meter can measure 10 channels, meeting the stability and accuracy testing of 25 power supplies.

In terms of control, all power supplies can be connected to the switch through network interfaces, achieving network synchronization control. Therefore, through the network, remote control operations such as power on, off, and current up and down can be achieved for all power supplies, improving the efficiency of batch testing (Figs. 6, 7).

Power performance testing

The technical parameter of HEPS high precision and stability power supply is shown in Table 1. All performance and parameter in the power supply test must meet technical

Table 3 Current calibration of HEPS high precision and stability power supply

Set	Before calibration	After calibration	Accuracy (relative to I_N) (ppm)
110A	110.212A	109.999A	4.3
130A	130.260 A	130.001A	4.3
150A	150.311A	150.002A	8.7
170A	170.359A	170.001A	4.3
190A	190.408A	189.998A	8.7
210A	210.460A	210.002A	8.7
230A	230.508A	230.003A	13

requirements. The testing process adopts the overall testing

Table 4 Current repeatability test

	I_1	I_2	225A
I_{avg} (A)	115.218188	184.367479	225.457449
I_{avg} (A)	115.217896	184.367457	225.457645
Repeatability (ppm)	2.53	0.12	0.87

of the power supply and rack, while measuring whether the performance of the power supply, DCCT, and rack meets the standards. The testing process also requires completing the coefficient calibration of the power supply and continuous work for 72 h. Table 1 shows the technical parameter of HEPS high precision and stability power supply.

The calculation formulas for stability, accuracy, and repeatability are shown in Table 2.

The stability test mainly tests the average of the output current of the power supply after continuous operation for 8 h. The stability curves of the 260A/45 V and 230A/25 V power supplies tested at 80% of output are shown in the following figure. After calculation, the stability is 5.22 ppm and 6.39 ppm, respectively (Fig. 8).

Accuracy is the measurement of the error between the actual output current and the given current. The actual output current needs to be calibrated before it can be compared. Use standard sensors to calibrate the ADC and feedback sensor coefficients of the power supply, and replace the original ADC sampling coefficients with the calculated "slope" and "intercept" to reduce the output current error, so that the error between the actual current value and the given current value is within a certain range (Table 3).

Repeatability testing mainly measures the consistency of the output current of the power supply at different intervals of time. Firstly, measure the average output current for

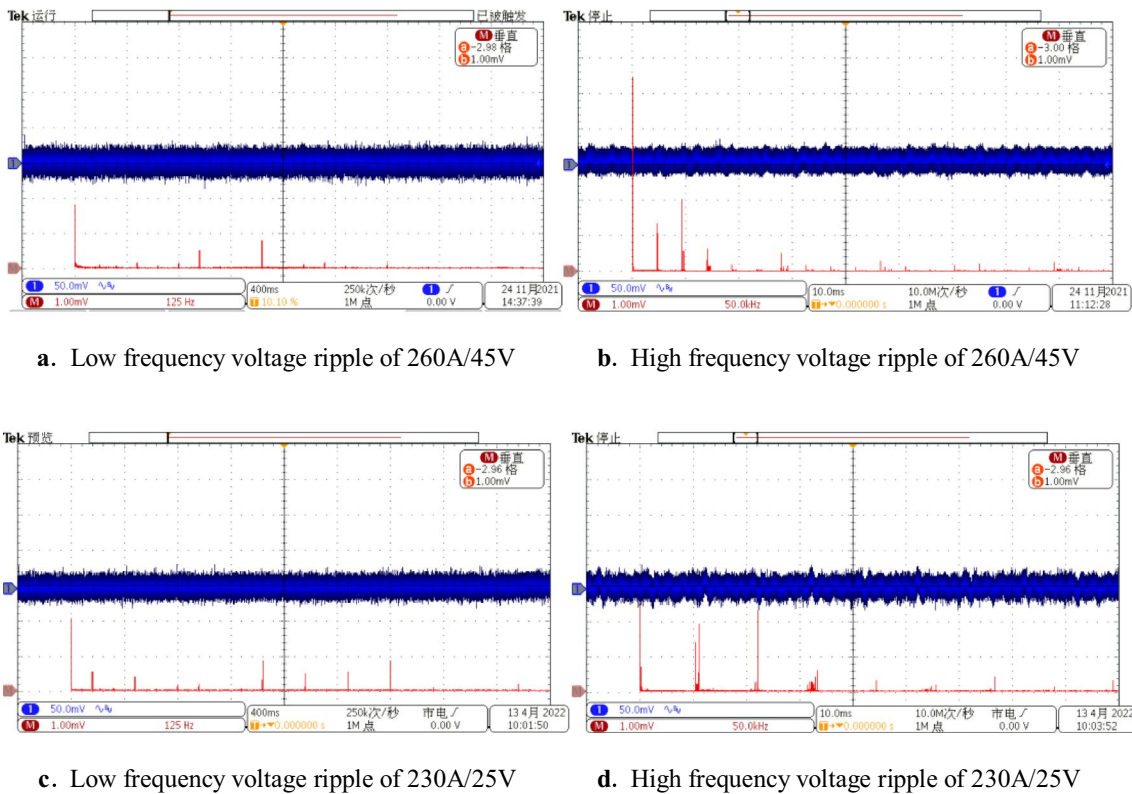
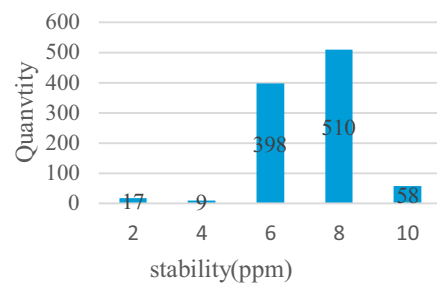
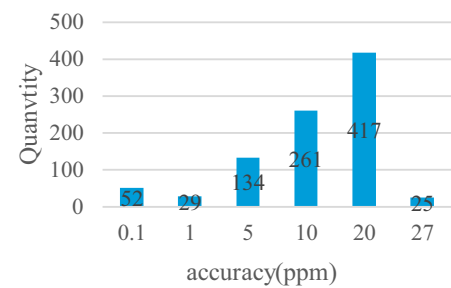
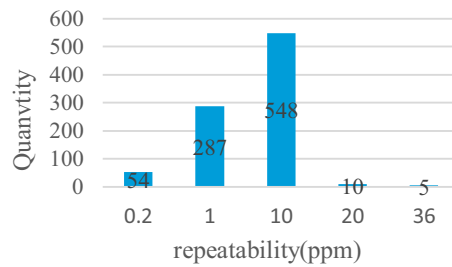
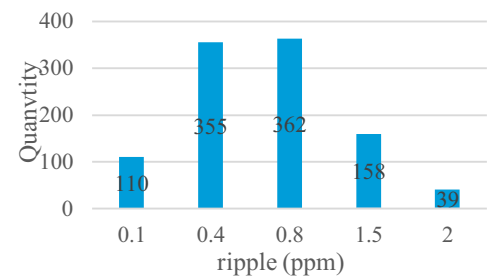


Fig. 9 Voltage ripple of two types of power supplies

Fig. 10 Distribution of results from batch testing**a.** Overall distribution of stability**b.** Overall distribution of accuracy**c.** Repeatability overall distribution**d.** Voltage ripple overall distribution

a fixed period of time (30 min), then turn off the machine, and hold for 30 min. Set the current again to the same current value as before, and calculate the average of the two currents to obtain repetitive data (Table 4).

The voltage ripple test is to directly observe the high-frequency and low-frequency ripple of the output voltage with an oscilloscope, and obtain the effective value of the ripple voltage through Fourier analysis. We tested the low-frequency and high-frequency ripple of the output voltage of 260A/45 V and 230A/25 V power supplies under 80% load (Fig. 9).

Test data statistics

The stability, accuracy, repeatability, and voltage ripple distribution of all tested power sources are shown in the figure. All data tested at 80% rated current (Fig. 10).

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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