Application of a precision programmable DC power supply for spectrometer calibration

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Abstract. The paper presents the circuitry solutions on the basis of which a precision programmable DC power supply was created and tested. The principle of operation of the DC power supply uses a high-precision method of controlling a pulse current stabilizer, based on the adaptation of the duty cycle of the pulse-width modulation (PWM) signal to control the inverter when the load mode changes. From the output of the inverter, the signal is converted by the rectifier into a DC signal with subsequent smoothing of the ripple and enters the load circuit. From a precision low-resistance shunt connected to the load circuit, the signal through the ADC in digital form enters the control unit (CU), implemented on the basis of FPGA, which has a embedded programme for controlling the voltage / current stabilization modes in the load circuit. In addition, the paper shows the use of a precision programmable DC power supply for solving the problem of calibrating the BTC-110S spectrometer. The block diagram of the test stand for spectrometer calibration is presented and relations for the correction of the recorded signals of the thermal radiation spectrum of the objects under study are derived.

1. Introduction

When designing and implementing optoelectronic measuring software and hardware systems, for example, at the stage of calibrating spectrometers that record the spectra of thermal radiation of heated bodies or, for example, gas-thermal particle flows, high requirements are imposed on the calibration accuracy [1–5]. To ensure high accuracy in the calibration of spectrometers, it is necessary to use etalon radiation sources. In order to ensure the minimum calibration error, as a rule, a precision, highly stable DC power supply is used to power the etalon radiation source (radiation calibrator). Requirements for the calibration accuracy are constantly increasing, and therefore for the accuracy and stability of the output voltages/currents of power supplies, so the development and creation of a precision-class DC power supply remains an urgent task. There are various universal solutions [1–5], laboratory and industrial instruments, however, they do not always satisfy a certain threshold of precision accuracy. Therefore, the authors of the paper developed their own version of a precision programmable DC power supply, which allows for its modernization and expansion of functionality.

To solve this problem, a high-precision method for controlling a pulse current stabilizer [6] is used, based on the adaptation of the duty cycle of the pulse-width modulation (PWM) signal to control the inverter when the load mode changes. On the basis of a high-precision method of controlling a pulsed current stabilizer [6], a precision programmable DC power supply was developed and tested, operating...
in two stabilization modes (in the stabilization mode of the output constant current and in the stabilization mode of the output voltage [7]). Switching from one mode to another is carried out by a toggle switch on the instrument panel. The DC power supply was modernized [8] in order to improve its technical characteristics.

2. The principle of device operation and the main circuitry solutions

Figure 1 shows a block diagram of the programmable DC power supply.

![Block diagram of the precision programmable DC power supply](image)

Let's briefly explain the principle of operation of the precision programmable DC power supply.

The first block of the DC power supply, the input of which is supplied with a voltage of 220 V at a frequency of 50 Hz from the AC mains, is a low-frequency lowering voltage transformer 1. From the output of the transformer, an AC voltage (up to 18 V) is fed to the input of a rectifier 2 with a filter that smooths out pulsations. From the output of the rectifier with filter 2, the signal is fed to inverter 3. Taking into account the duty cycle of the control PWM-signal coming from unit 12, a pulse signal is generated at the output of the inverter, which is directly fed to the second rectifier 4. Rectifier 4 converts the pulse signal from the inverter output into a DC signal, which is then smoothed by the output filter 5 and fed to the load circuit (low-resistance four-terminal resistor - shunt 6 and the main load resistance 7 of the external consumer). Shunt parameters: resistance 0.001 Ohm, relative error no more than 0.001% and power 5 W. The voltage from the shunt 6, proportional to the current flowing through it, is fed to the ADC 10 through the preamplifier 9. The preamplifier 9 converts the voltage taken from the shunt 6 to the required level in accordance with the dynamic range of the input voltage on the ADC 10. The discrete value of the output voltage of the ADC 10 is transmitted to the "control unit (CU)" 12, where it is converted into a digital current value. In addition, the CU programmatically using prediction algorithms determines the numerical estimate of the duty cycle of the PWM-signal to control the inverter, transmits it to the digital PWM-controller implemented as part of the CU 12. The PWM-controller generates a square wave signal to control the inverter 3.

At first, block 12 implemented a 13-bit capacity and theoretically it made it possible to control the voltage in the load circuit with a step of approximately 0.003 V at a maximum of 24 V, and in terms of
current – with a step of 0.004 A at a maximum current in the load circuit of 30 A. In practice, a TRU 1100–2350 incandescent lamp was used as a etalon source of thermal radiation (radiation calibrator), for which the guaranteed value of the minimum error in setting the lamp temperature is ensured by the minimum error of the constant current of the lamp supply of about 0.001 A. Therefore, in order to achieve the resolution on reinstallation the current value to 0.001 A, it was necessary to raise the bit capacity of the PWM-controller to 15 bits (the maximum ability to set the bit capacity is 16 bits).

Control, installation and correction of signals is carried out by a program embedded into the architecture of the FPGA, which is part of the control device 12.

Consider the block diagram of the CU 12 shown in Figure 2.

![Figure 2. Block diagram of the CU for a precision programmable DC power supply](image)

**Figure 2.** Block diagram of the CU for a precision programmable DC power supply: COM port – serial interface RS-232; LCD – liquid crystal display; LED – set of two LEDs indicators; FPGA – field-programmable gate array; Buttons – voltage/current setting buttons; ADC – analog-to-digital converter; Coolers – three fans for cooling the precision programmable DC power supply; Temperature sensor – sensor for temperature measuring of the elements inside the precision programmable DC power supply body; Relay – power relay for connecting (or for disconnecting) a current transformer to a AC network 220 V.

The precision programmable DC power supply is connected with a cable to a socket of 220 V and 50 Hz. Inside the DC power supply case, the power cable is split into two cables. One cable is connected to the input of a stabilized AC-DC power supply mounted in a separate small case (not shown in the Figures) with two output voltages. One DC voltage of 5 V is used to power of logic and digital microcircuits, and another DC voltage of 12 V is used to power of coolers (cooling fans). The second 220 V mains voltage cable is connected through the power relay ("Relay" in Figure 2) to the current transformer 1 shown in Figure 1.

After pressing the power button on the front panel, the microcircuits are initialized, the minimum duty cycle of the PWM-signal is set and one of the two stabilization modes (voltage/current) is expected to be selected. Then the setpoint voltage/current is set in the load circuit.

After initializing the microcircuits and setting the specified voltage value (or current value) in the load circuit, the relay closes, the power part of the circuit begins to function and current appears in the load circuit. By pressing the “on/off” button of the DC power supply (on its front panel), the current in the load circuit can be “zeroed”, since the power relay will open. Zeroing of the current in the load circuit due to the opening of the power relay will occur on a command from the program embedded into the FPGA, if the critical temperature value transmitted to the program from the temperature sensor is exceeded. This eliminates the possibility of fire in the DC power supply.

FPGA, as the main computing and control "core" of the DC power supply, in parallel receives from some units and transmits data to other units, namely:
- reads signals when pressing the buttons for setting the voltage/current values – manual setting of the voltage/current values is carried out by the user from the front panel of DC the power supply;

- reads the values from the ADC (Figures 1 and 2) and compares them with the voltage/current values that were set using the control buttons. According to the comparison results, if necessary, the values are corrected by the control PWM-signal;

- it signals two states by means of two LEDs: a) the LED on the instrument panel signals the “on/off” state of the precision programmable DC power supply; b) the second LED, located inside the case opposite the slot in the case, thus viewed from the outside of the DC power supply, signals the state “presence/absence of current in the load circuit”;

- reads the temperature value of the elements inside the DC power supply case from the temperature sensor. If the upper temperature threshold is exceeded, it turns on the cooling fans. If the lower temperature threshold is underestimated, it turns off the cooling fans;

- displays on the LCD the values of three signals simultaneously: voltage across the load resistance; current flowing through the load circuit; temperature of the elements inside the DC power supply case;

- controls the power relay, which closes/opens the circuit of current transformer 1 (Figure 1);

- reads and sends data via COM port to PC.

In order to automate a series of experiments on the calibration of spectrometers and other optoelectronic measuring systems (control of the DC power supply, registration and storage of data on a PC), a program was developed that was installed on a PC and designed to control a precision programmable DC power supply.

The program has the following functionality:

- sends to the CU of the DC power supply a command to maintain the stabilization mode of the output voltage on the load resistance, or the mode of stabilization of the current in the load circuit;

- sends to the CU of the DC power supply a command to set a user-specified voltage value or current value in the load circuit;

- having received the temperature value of the elements inside the DC power supply case from the DC power supply itself, the program displays this temperature value on the PC display in real time;

- having received from the DC power supply the values of voltage across the load resistance and the current in the load circuit, displays these values on the PC display in real time;

- the program allows you to select the method of setting the voltage value set by the user at the load resistance: a) method (mode) of "fast" setting the set value (in one tuning step); b) method (mode) of "smooth" voltage change across the load resistance to a given value (the desired value is set in several steps by step-by-step build-up to a given voltage value with a small voltage increment value).

The mode of smoothly changing the voltage across the load resistance up to a given value is an extremely important and necessary way of regulating the dynamics of changing the load parameters. The following circumstance is meant. If the current through the TRU 1100-2350 etalon lamp is abruptly changed in a short time to the maximum values (up to 30 A), then the lamp may be “damaged” and become unusable for its further use. The method of "smooth" increase in voltage (or current) in the load circuit is carried out by introducing a PID-controller into the control logic [8].

To control the DC power supply using a PC program, a protocol of commands was developed, which are decoded by the program embedded into the FPGA, and then the actions corresponding to these commands are performed. This approach is convenient for its versatility, since a COM port is used for exchange. That is, you can open any terminal and send control commands that have intuitive abbreviations.

For example, to set the voltage values at the load resistance, you need to send the command "su06.750", which will set the voltage to 6.75 V at the load resistance. To receive the temperature value of elements inside the DC power supply case by the PC program, you need to send the “gt” command, and in response the program will receive the temperature value in degrees Celsius. On the display of the DC power supply and in the PC program (upon relevant requests), the temperature values and real values of voltage/current on the load are updated after one second (Figure 3). This is enough to get up-to-date data.
Figure 3. Programming interface for controlling the precision programmable DC power supply.

A number of experiments were carried out: 1) on the stability of the installation (and reinstallation) and maintaining the exact setpoint voltage/current; 2) the check for the absence of overheating of the output circuits of the DC power supply, provided that high voltage/current values are set; 3) tests were carried out with a TRU 1100-2350 etalon lamp at maximum wattage.

The DC power supply has the following main output characteristics: maximum DC voltage 24 V, maximum DC current 30 A. It was required, if possible, to test the DC power supply in all ranges. Initial testing of the DC power supply was performed using miniature 12 V, 50 W incandescent bulbs. First, one lamp was connected, then two lamps were switched on in parallel, then three and four lamps each, thereby increasing the load current within 6-24 A, and the voltage within 1-12 V. When testing the TRU 1100-2350 etalon lamp, long and varied tests were required, since the current through the TRU 1100-2350 lamp reached 25 A and an increase in the current through the lamp required smooth loading so as not to damage it by sudden current/voltage surges.

For the TRU 1100-2350 etalon lamp, the "calibration" dependence of the temperature $T$ on the current $I$ flowing through it is known, which we denote as $T = f(I)$.

For experiments on the calibration of the BTC-110S spectrometer, a corresponding test stand was created (Figure 4).

![Figure 3](image1.png)

**Figure 3.** Programming interface for controlling the precision programmable DC power supply.

![Figure 4](image2.png)

**Figure 4.** Block diagram of the test stand for BTC-110S spectrometer calibration.

At the test stand, the hardware and software complex for recording the thermal radiation spectrum (Figure 5) includes: 1 – BTC-110S spectrometer; 4 – precision programmable DC power supply (Figure 6); 5 – personal computer (PC). The luminous flux of thermal radiation from the etalon radiation source 3, for example, in our case from the TRU 1100—2350 etalon lamp, is focused through the lens 2 to the input of the BTC-110S spectrometer, which, due to the presence of a diffraction grating in its composition, projects the thermal radiation spectrum (from the etalon radiation source 3) onto the CCD linear array. The CCD linear array is also included in the BTC-110S spectrometer. The
digitized spectrum signal is transmitted to the PC through the interface circuit of the spectrometer, where it is processed and stored on the PC disk using the special software created.

To control the registration of spectra and their processing, special software was created [9].

**Figure 5.** A sample of the thermal radiation spectrum recorded by the BTC-110S spectrometer.

The thermal radiation spectrum (Figure 5), recorded by the BTC-110S spectrometer in one of the experiments on the test stand (Figure 4), contains multiplicative nonlinear distortions caused by the instrumental distortion function of the optoelectronic chain of the spectrometer recorder. Mainly, the main contribution to these distortions is made by the diffraction grating and CCD linear array of the BTC-110S spectrometer. In addition, the spectrum signal contains additive noise that can be significantly reduced by various filtering and suppression methods. The recorded spectrum of thermal radiation from the TRU 1100-2350 etalon lamp (the emitter in it is a tungsten plate), taking into account the instrumental distortion function of the optoelectronic chain, can be written in the form

\[ B(\lambda, T) = \gamma(\lambda) \cdot r(\lambda, T), \]  

(1)

where \( B(\lambda, T) \) is the recorded thermal radiation spectrum from the TRU 1100-2350 etalon lamp; \( \gamma(\lambda) \) is the instrumental distortion function of the optoelectronic chain of the spectrometer recorder; \( r(\lambda, T) \) is spectral density (emissivity, [10]) of the emitter (tungsten plate of the TRU 1100-2350 etalon lamp) presented in the "gray" body model

\[ r(\lambda, T) = \varepsilon(\lambda, T) \cdot \varphi(\lambda, T), \]  

(2)

where \( \varepsilon(\lambda, T) \) is the relative emissivity of the tungsten plate. The Planck function \( \varphi(\lambda, T) \) (emissivity of an "absolutely black" body) has the form

\[ \varphi(\lambda, T) = C_2 \lambda^{-5} \left( e^{\frac{C_2}{\lambda T}} - 1 \right). \]  

(3)

For tungsten, there are quite accurate tabulated values of the relative emissivity at various temperatures, for example, in the reference book [11].

Thus, the problem of calibrating the spectrometer is reduced to determining the instrumental distortion function of the optoelectronic chain of the spectrometer recorder. In test experiments, setting certain current values \( I_{\text{test}} \) in the circuit of the TRU 1100-2350 etalon lamp using the precision programmable DC power supply, the test temperatures will be known according to the calibration dependence \( T_{\text{test}} = f(I_{\text{test}}). \) The spectrometer will register the signal \( B(\lambda, T_{\text{test}}) \). Based on formulas (1)-(3), we write an expression for the function \( \gamma_{\text{cal}}(\lambda) \) that calibrates the spectrometer

\[ \gamma_{\text{cal}}(\lambda) = \frac{B(\lambda, T_{\text{test}})}{\varepsilon(\lambda, T_{\text{test}}) \cdot \varphi(\lambda, T_{\text{test}})}. \]  

(4)
Consequently, the function $\gamma_{cal}(\lambda)$ defined in test experiments will make it possible to correct the signals $B_{obj}(\lambda, T)$ of the thermal radiation spectrum of the object under study recorded by the BTC-110S spectrometer using the expression

$$r_{correct}(\lambda, T) = B_{obj}(\lambda, T) / \gamma_{cal}(\lambda).$$

(5)

The corrected signal of the thermal radiation spectrum makes it possible to solve, for example, the “inverse” problem of reconstructing the temperature distribution of particles in the gas-thermal flows of spraying the protective coatings on engineering products [12] and other problems [13–16].

Concluding the presentation of the methodological and theoretical foundations of the calibration of the spectrometer and measurements with it of the thermal radiation spectra of the objects under study, we will show in Figure 6 the appearance of the precision programmable DC power supply.

**Figure 6.** Appearance of the precision programmable DC power supply.

On the front panel of the DC power supply (Figure 6) in the upper right corner there are a power-on-off LED indicator and the on/off button of the DC power supply itself. From left to right (in the middle of the panel) there are: liquid crystal display (LCD), control buttons (setting user-specified voltage/current values) and a toggle switch for switching two stabilization modes (voltage or current stabilization in the load circuit). In the lower left corner, pairwise closed between each other output terminals for connecting an external load (power supply consumer) are fixed: a pair of closed “red” terminals corresponds to polarity with a “+” sign, and a pair of closed “black” terminals corresponds to polarity with a “−” sign. Using a pair of terminals for each polarity at the output of the DC power supply halves the current in each of the parallel-connected wires that go to the terminals, thereby reducing their overheating and avoidance of opportunity of electric cable fire at maximum currents (up to 30 A) in the load circuit.

### 3. Conclusions

A solution to the problem of creating a precision programmable DC power supply operating in two stabilization modes is proposed: in the voltage stabilization mode (in the range up to 24 V) or in the current stabilization mode in the load circuit (in the range up to 30 A). The minimum step for reinstallation the current values is 0.001 A, the ripple on the load is no more than 0.005 V. The possibility of using the programmable DC power supply together with a TRU 1100-2350 etalon lamp for calibrating the BTC-110S spectrometer is shown. The obtained expression for the instrumental distortion function of the optoelectronic chain of the spectrum recorder makes it possible to correct the
signals of the thermal radiation spectra recorded by the spectrometer in various experiments on studying the spectral properties of heated objects.

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