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# SUPERCONDUCTIVE COILS POWER SUPPLY

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# ИСТОЧНИК ПИТАНИЯ СВЕРХПРОВОДЯЩИХ МАГНИТОВ

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## АННОТАЦИЯ

Описывается источник тока до 200 А для сверхпроводящих магнитов с микропроцессорной системой управления. Источник допускает два вида регулирования: грубое ограничение входной трёхфазной мощности посредством симисторов, управляемых трёхфазным таймером на отдельном микропроцессоре, и плавная подстройка линейным регулятором на мощном MOSFET транзисторе.

Автоматическая система управления источником включает в себя режимы плавного ввода-вывода тока на заданной скорости, а также два детектора перехода катушек в нормальную фазу. Время реакции системы на сигнал с детектора не превышает 1 мс. Предусмотрен аварийный вывод тока из катушек при переходе в нормальную фазу.

## ABSTRACT

The power supply for superconductive magnets provides current up to 200 A. It has two level of regulation: rough cut down 3-phase power by triacs controlled by separate CPU and fine adjustment of the output current by linear regulator based on power MOSFET transistor.

Automatic microprocessor control system provides smooth current injection and extraction at the programmed speed. Besides, it’s equipped by two detectors of quenching of the coils that are used for emergency current extraction. Maximum reaction time of the system to detector signal is 1 ms.

## Introduction

The work has been done in the frame of ISTC[1] Project #1861 “Creation of the Universal Gas Polarized Target for the Investigation of the Nuclear Polarization in the Molecules of Hydrogen (Deuterium) at the Different Interactions with the Target’s Walls” (CELGAS).

Magnetic field in CELGAS experiment (Fig. 1) is used for guiding electrons and ions along the storage cell. This field is generated by two superconductive coils that allow producing up to 2 T field at 100 A current. The use of the superconducting coils is subject to the risk of quenching, i.e. a large amount of heat is dissipated damaging or even completely destroying the coils. Special power supply (SCPS – Superconductive Coils Power Supply) was designed and built to provide stable current up to 200 A and protect coils in case of quenching.

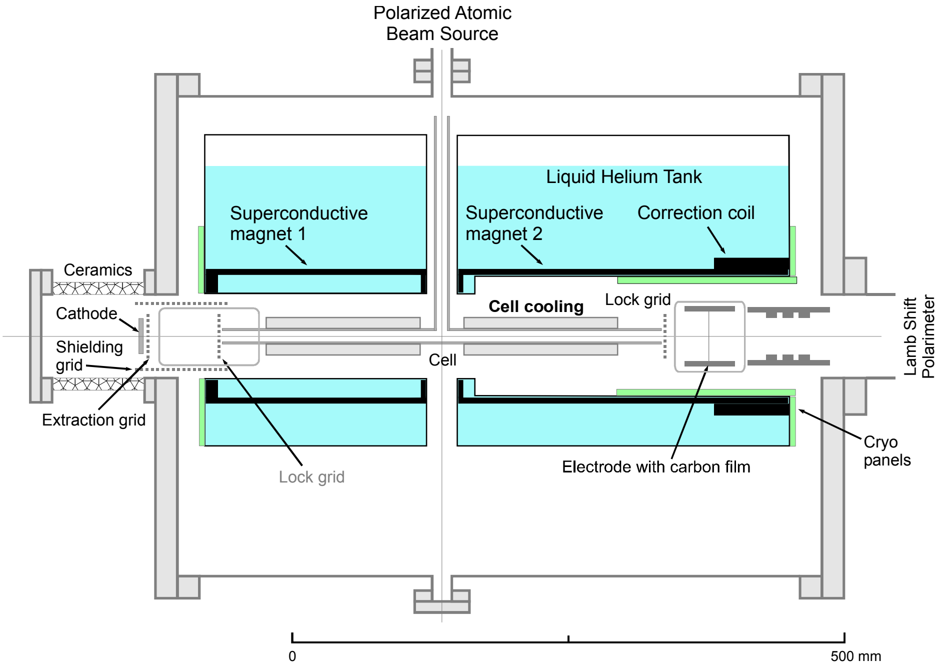

Fig. 1. CELGAS experiment setup layout

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[1] International Science and Technology Center

Superconductive coils are connected serially to current supply. Each of them has superconductive switch that could close the current loop with the coil. Thus current could be frozen in the each particular coil (Fig. 2). Besides, every coil is equipped by a 0.5 Ω resistor mounted on the coil side to protect the coil from blowing up during quenching. Most of the energy frozen in the coil dissipates in this resistor during transition of the superconducting coils to normal state. Coupler loop is installed at the end of every coil to provide quenching signal for protection circuit of the power supply.

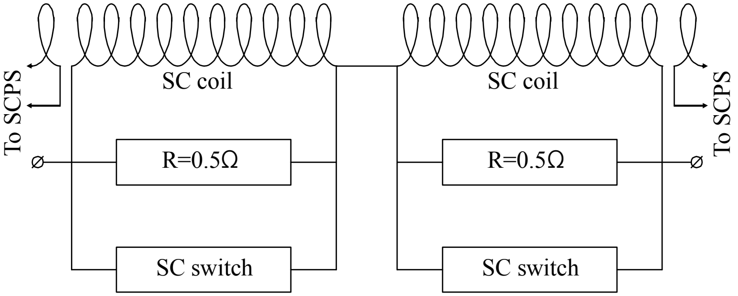

Fig. 2. SC coils connection schematic

SCPS was designed to supply two coils with the same current, but the working currents in the coils could be frozen different. Protection loop for each coil is separate. In case of quenching of the coils power supply breaks the superconductive loop by heating of superconductive switch and connects external ballast resistor to suppress heat release in the helium vessel.

The current supply must have intelligent current control algorithms to inject required current to flow coupled coils because any change of current in one of these coils affects the current in the others.

## Power supply

Current supply (Fig. 3) uses 3-phase power. High efficiency is achieved by using two levels of current stabilization. First, control board roughly cut down 3-phase power by triac PWM regulator based on the Atmel AT89C2051 microcontroller. Power restriction setpoint comes from main CPU. Second, fine adjustment of output current is made after rectifier by a linear regulator making use of power MOSFET transistor. Control signal for this transistor is generated from the current shunt signal and control signal from 16-bit DAC.

The distinctive advantage of the power supply is so-called 6-phase two-halfperiod rectification of the alternating current. This allows to achieve output current modulation less than 1.5 % at the maximum output current of 200 A. Ripple frequency is 600 Hz which is easily suppressed by LC-circuit. Primary windings of the power transformer are connected by a "star" scheme. Three secondary windings with $N_2$ turns each are connected by a "star" scheme to the Larionov's [1] rectifier. Another three secondary windings with $N_3 = \sqrt{3}N_2$ turns each are connected by a "triangle" scheme to the second Larionov's rectifier. Similar outputs of the both rectifiers are merged together. Both rectifiers are based on 3-phase diode bridges 160MT120KB (International Rectifier) with a maximum current of 160 A.

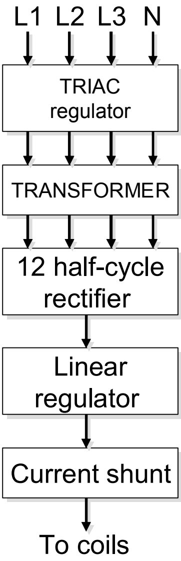

Fig. 3. Current supply

One of the most important elements of SCPS device is quenching detectors. They should detect spontaneous transitions of the coils from superconducting state to normal. The coupler loop is installed near each of the magnet. They are inductively coupled with the magnets. Main coil and coupler loop are connected to the bridge scheme in opposite directions. Differential signal in the bridge scheme is balanced by a trimmer (Fig. 4) and then comes to amplifier $A_1$.

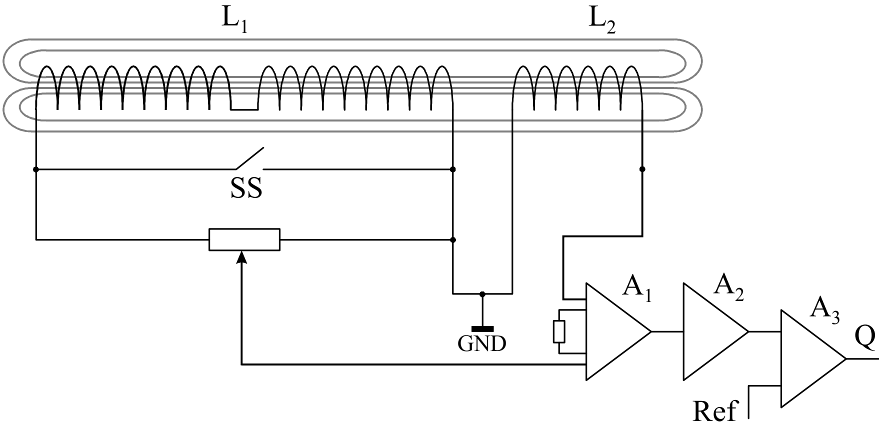

Fig. 4. Quenching detector

There are three modes of operation:

- current injection to superconducting coils
- current removal from superconducting coils
- permanent operation with frozen current.

During the current injection superconducting switch (SS) is open. Voltage at the ends of coil $L_1$ is proportional to current injection speed:

$$\varepsilon_1 = -L_1 \frac{\partial I_1}{\partial t}.$$

For the coupler loop the voltage is:

$$\varepsilon_2 = \frac{L_1 L_2}{M} \frac{\partial I_1}{\partial t},$$

where $I_1$ – current through $L_1$, $M$ – mutual inductance factor.

These voltages are summarized at the differential amplifier $A_1$. The result will have different sign for current injection and removal. RMS to DC converter $A_2$ is used to get absolute value of the signal, which then is compared with the threshold on the comparator $A_3$. Threshold value is chosen to get required sensitivity at the typical current injection or removal speed. Quenching of the coil during current injection does not affect voltage of the coupler loop because current in the coil is supported by the source, but voltage of the main coil will be changed because of the voltage drop on the normal wire. This will cause change in the bridge signal which could exceed threshold value. Therefore comparatore will generate quenching signal Q processed by the main CPU. Quenching in frozen current mode is processed in a similar way.

All ballast resistors and power components like current shunt and MOSFET transistor are mounted on water-cooled heat exchanger. Temperature of this heat exchanger is measured by control board and produces overheating alarm.

## Control board

SCPS control board (Fig. 5) is based on the Atmel AT89S8252 microcontroller running at 22.1184 MHz clock frequency. It has 8Kb static RAM to keep all data. CPU has external watch-dog, which attends to controller program faults and resets CPU as fast as in 0.5 s in this case.

Separate AT89C2051 micro-controller handles 3 phase PWM regulation. It takes setpoint from the main CPU via serial connection and uses internal timer and phase synchronization signals for regulation. Every phase is regulated independently. In case of missing synchronization signal of any phase all three phases are blocked. This mode of regulation is rough but it saves power and, consequently, allows one to work without water cooling.

Control signals for superconductive switch heaters and 3 phase switch go through buffer [ULN2803] to solid state relays on a separate board. Current regulation signal and setpoints for coil signals come from 16-bit DAC [DAC7634].

All analog signals from sensors come to 16-channel multiplexer and then go through AD711 amplifier to 16-bit ADC [ADS7807]. These signals are:

1. Amplified differential signal from coil 1.
2. Amplified differential signal from coil 2.
3. Amplified signal from current shunt.
4. Direct signal from coil 1.
5. Temperature sensor 1.
6. Temperature sensor 2.
7. Temperature sensor 3.
8. Temperature sensor 4.
9. Temperature sensor 5.

10-16. Additional analog inputs (±10V).

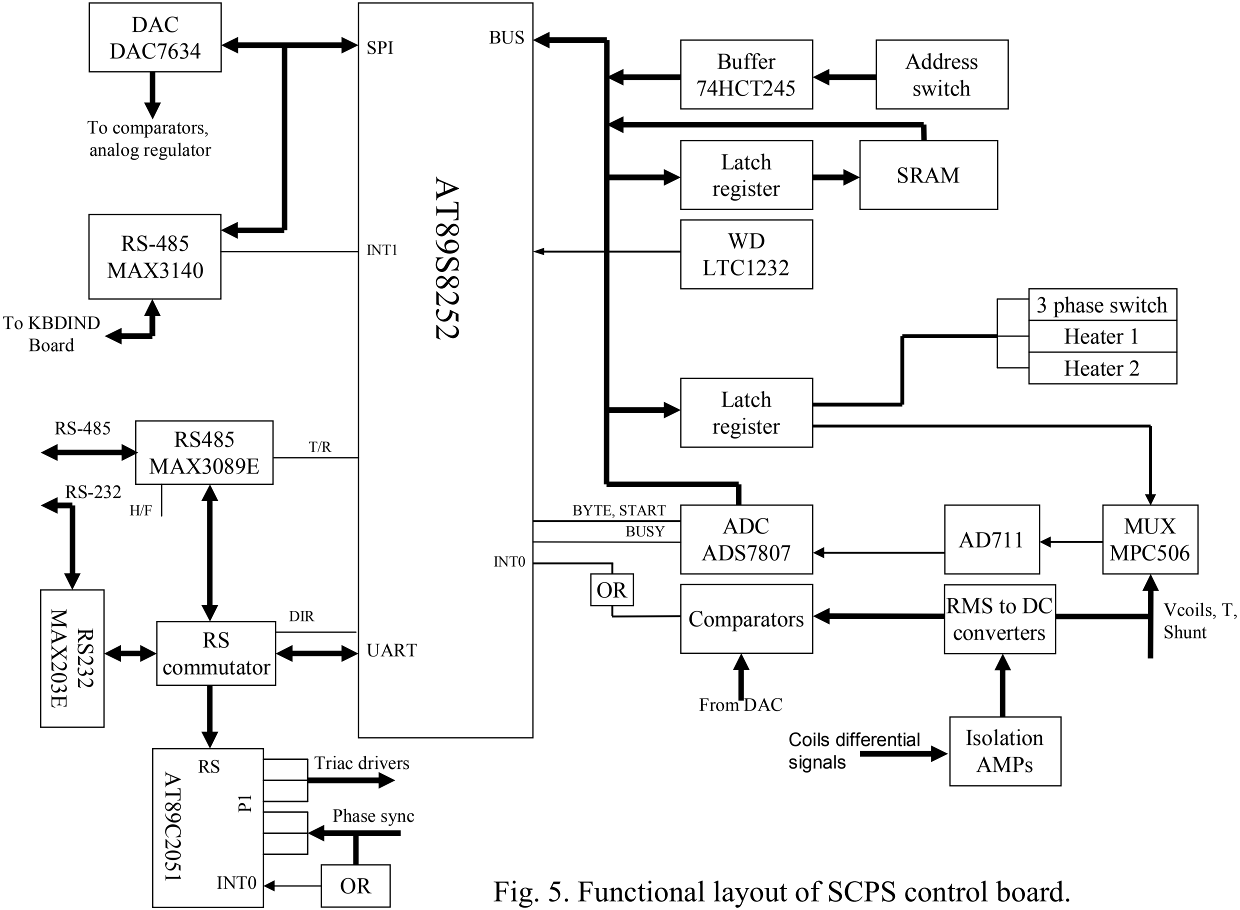

Fig. 5. Functional layout of SCPS control board.

Control board is equipped by RS-485 and RS-232 serial interfaces and could be connected to the slow control system. SCPS itself does not have any indicator or control panel because it is planned to be installed at the bottom of electronic rack. But in addition to computer serial interface control board has special RS-485 serial link to connect external indicator and control panel.

The device is equipped by an external indicator and control panel and has digital RS-232 (RS-485) interface, which allows it to be included into common slow control system.

## Controller software

Controller software is written in C language. It provides reading of 16 sensors with programmed averaging by 1-255 samples, handles communication with the host computer. Communication with the host computer is interrupt-driven, so any serial data exchange does not affect seriously sensors reading procedure.

Software responds to alarm interrupt which comes from the superconductive coils quenching detector. This signal cause software to read both coils differential signals with averaging by 8 samples and break corresponding superconductive switch and 3-phase power in case of alarm. Audible alarm is also generated. Software thresholds for these alarms are programmed by host computer as well as hardware threshold for comparators generated by DAC.

Controller also watches heat exchanger temperature and generates interrupted audible signal if it goes above specified threshold.

Quenching process in superconductive coils is usually fast. Coils differential signal rises in tens of milliseconds. It is not possible to transfer such a dataflow to the host computer in real time. To investigate this process a special mode in the controller was implemented. In this mode, controller starts accumulating ADC history for first 5 channels in its static memory (see SCPS test with coils below). This enables to obtain fast shot of the first 5 ADC channels with total time of 550 ms and samples period of about 0.7 ms.

## Serial protocol

Communication protocol for all our devices consists of two main commands: read memory byte and write memory byte. It could contain also some special commands which are described separately for every device. Protocol is based on 5-byte binary packets exchange (Table 1). The device sends 5-byte answer for every 5-byte command, if device address field and XOR-sum in this command is correct.

*Table 1*

*Serial protocol command structure.*

| Byte | Description |
|---|---|
| 1 | 6-bit device address. Should be equal to device address set on the dip switch inside the device or packet will be ignored otherwise. Two most significant bits are ignored. |
| 2 | Bit 7 – read/write bit. Bit 7 = 1 corresponds to write command and bit 7 = 0 – read command.<br>Bit 6 – special command flag. If bit 6 = 1, packet contains special command.<br>Bits 5÷0 – high bits of 14-bits address field. |
| 3 | Low byte of 14-bits address field. |
| 4 | Data byte. |
| 5 | XOR-sum of first 4 bytes. B5=B1^B2^B3^B4. If it is not correct XOR-sum, packet is ignored. |

This protocol makes it possible to represent any serial device as a array of bytes with transparent access to process variables. Once implemented, such a protocol could be used with any device of this type. The only thing user should know about it is controller memory map, which is of course different for every device, and device address. Byte ordering is little endian, high byte has low address. This requires all word

(16-bit integer) and float variables to be swapped in the IBM compatible PC, that use big endian byte order.

Communication parameters are always 8-bit with 1 stop bit, no parity, no flow control. Baudrate could be selected from 9.6, 19.2, 57.6 or 115.2 Kbit/s by dip switch inside the device (Table 2). Usually read or write access to the device memory using this protocol takes not more than 2ms for every byte at 115.2 Kbit/s.

Data format in this protocol allows one to access a number of devices making use the same continuous address space with 3-byte address.

Examples:

**1.** Host computer wants to read byte at address `0x345` from the device with address `0x02`. Device memory contains `0xAA` at this address. Note that this is NOT an ASCII strings, but binary bytes.

```
host request    : 0x02 0x03 0x45 0x00 0x44

device answer   : 0x02 0x03 0x45 0xAA 0xEE
```

**2.** Host computer wants to write byte `0x55` at address `0x1543` to the device with address `0x08` (Note that read/write bit is cleared in the answer).

```
host request    : 0x08 0x95 0x43 0x55 0x8B

device answer   : 0x08 0x15 0x43 0x55 0x0B
```

*Table 2*

*Configuration switch.*

| Switch position | Description (0=OFF, 1=ON) |
|---|---|
| 1-6 | 6-bit device address in binary format. Least significant bit is selected by switch position 1. Valid range is 1÷63. |
| 7-8 | Communication speed:<br>00 – 9600 bit/s<br>01 – 19200 bit/s<br>10 – 57600 bit/s<br>11 – 115200 bit/s |

Most of serial controllers accepts some special commands. The first one is “read all memory” command. For this command byte 2 of the serial packet should be 0x41 (0x40 sets bit 6, 1 is the command number). Bytes 3 and 4 define high and low bytes of maximum address correspondingly. In response to this command device sends all memory contents from address 0 to maximum address specified in the command as a continuous flow of bytes without prefixes and checksum. This command is fastest way to get all values from the device. For example, reading of all SCPS parameters byte by byte takes about 130 ms while using 0x41 command reduces this time to 40 ms.

Other two commands apply to all devices on the RS-485 bus without addressing. These are “shut up” and “wake up” commands. They are necessary if communication software needs access to serial device with different protocol, for instance, ASCII-based. In this case some ASCII commands could be recognized by our serial device and it will occupy the bus with the answer. Thus, all our devices should keep silence during data exchange with other equipment. Normal commands handling could be then restored by “wake up” command.

```
Shut up command : 0x02 0x03 0x45 0x00 0x44

Wake up command : 0x02 0x03 0x45 0x00 0x44
```

Devices don’t response to these commands. They just enable or disable normal communication protocol.

## Memory map

Internal controller variables are read as a byte arrays independently of their type. Controller supports three base types:

- byte (equivalent to char) – 8 bit integer
- word – 16 bit integer
- float – 4-bytes single precision floating point value according to IEEE 754 standard [2].

Byte ordering inside controller is little endian, high byte has low address. This requires all word and float variables to be swapped in the IBM compatible PC, that use big endian byte order.

SCPS variables types and location is shown in Table 3. To increase data processing speed, controller doesn’t work with floating point variables. All parameters are integer. ADC values could be converted to voltages by the formula: V[i]=ADCval[i]/0xFFFF*20-10. DAC values are adjusted for full performance by amplifiers of the current shunt signal and the differential coils signals. In that way full scale DAC value (0xFFFF) for current regulation corresponds to the maximum current of the device, 100 A.

*Table 3*

*Memory map.*

| Address | Length | Type | Name | Description |
|---|---|---|---|---|
| 0x0000 | 2 | word | WDCount | Watch-dog resets counter. Should be 0 or small value and not increase. This counter resets to 0 at every “cold” start, i.e. power-on procedure and increases at every watch-dog CPU reset. |
| 0x0002 | 1 | byte | L1Byte | Reserved. Do not write. |
| 0x0003 | 1 | byte | Flags | Bit flags:<br>Bit 0 – Speaker control. If set, speaker is on.<br>Bit 1 – Alarm processing. If set, SCPS handles coil detector alarms.<br>Bit 2 – Alarm trigger. Controlled by alarms handler.<br>Bit 4 – Temperature alarm speaker control. Same as Bit 0. |

| Address | Length | Type | Name | Description |
|---|---|---|---|---|
| 0x0004 | 1 | byte | ADCchan | ADC channel number. Device will measure only this channel (0÷15) or all 16 channels if ADCchan>15. Does not affect alarm processing. |
| 0x0005 | 1 | byte | MuxAddr | Reserved. Do not write. |
| 0x0006 | 1 | byte | ToIndCntr | Reserved. Do not write. |
| 0x0007 | 1 | byte | AVG | Number of samples to average. No averaging occurs if = 0. Default value is 0. |
| 0x0008 | 1 | byte | Delay2051 | Triacs current control value. Do not write. |
| 0x0009 | 1 | byte | SP_2051 | Triac control setpoint. |
| 0x000A | 1 | byte | Clock1 | Timer period in 25ms intervals for temperature alarm beeping. |
| 0x000B | 1 | byte | TriacSpeed | Changing speed of triac control value. |
| 0x000C | 1 | byte | CurrentSpeed | Changing speed of current control value. |
| 0x000D | 2 | word | Cur_SP | Current setpoint. |
| 0x000F | 1 | Byte | ID | Device ID = 0xA2. It is NOT device address. |
| 0x0010 | 8 | word | DACval[4] | DAC control values. Use only DAC[1] and DAC[2] for alarm setpoints. DAC[0] and DAC[3] changed automatically. Do not write them. |
| 0x0018 | 4 | word | QCHTrsh[2] | Software alarm thresholds. |

| Address | Length | Type | Name | Description |
|---|---|---|---|---|
| 0x001C | 1 | byte | CMDByte | Command byte:<br>Bit 0 – 3 phase power control. If set, power is on.<br>Bit 1 – Heater control for superconductive switch 1.<br>Bit 2 – Heater control for superconductive switch 2. |
| 0x001D | 1 | byte | CMDByte1 | Reserved. Do not write. |
| 0x0020 | 32 | word | ADCval[16] | Sensor values in 2-byte integer form. Voltage should be calculated by the formula:<br>V=ADCval/0xFFFF*20-10 |
| 0x0040 | 2 | word | AlarmT | Temperature setpoint for alarm. |

## Test with coils

Test and adjust procedures of SCPS were done on two superconductive coils which produce 2 T magnetic field at 100 A current. Basic algorithms like smooth current injection and extraction were tuned. To investigate the coils quenching process and adjust SCPS quenching detector ADC history mode was used.

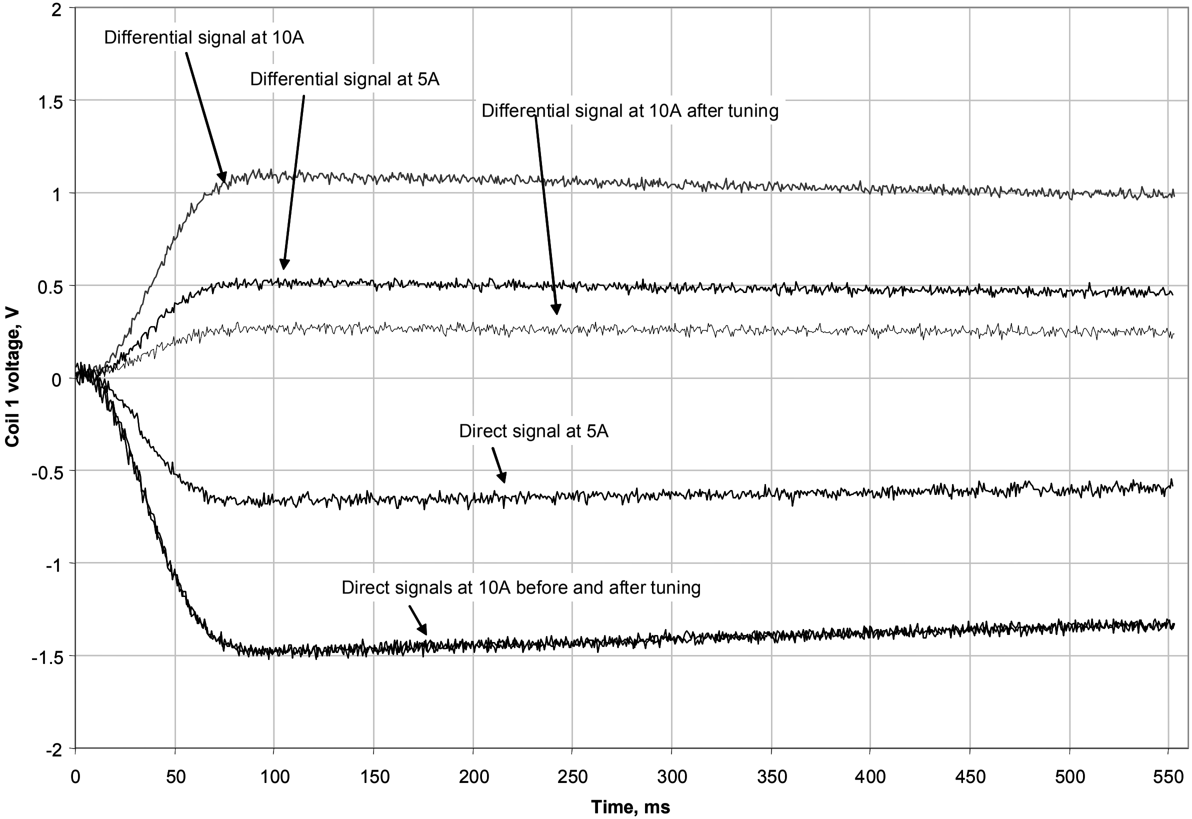

Fig. 6. Coil 1 voltage after current cut off.

For these tests, we injected 10 A or 5 A current to the coil and switched it off instantly with synchronous start of history accumulation. So origin of the time axis corresponds to current cut off. Results are shown in Fig. 6. Adjusting the amplifier of differential signal for the alarm detector does not affect direct signal amplitude. These tests are also useful to measure typical transition time of the coil. In our conditions it takes about 60-70 ms for the coil to release all conserved energy. This is slow enough for SCPS controller to take some corrective actions like heating superconductive switch.

## References

[1] Istochniki elektropitaniya radioelectronnoi apparatury. Radio i svyaz. 1985.
[2] IEEE Computer Society (1985), IEEE Standard for Binary Floating-Point Arithmetic, IEEE Std 754-1985.