Novel Supplies for Powering a Superconducting Magnet

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Abstract—**A family of new supplies for powering superconducting magnets was developed in our institutes. As an example, two supplies are described in the paper. One of the supplies uses superconducting, another – semiconductor-based repetitive switches. Both supplies are able to generate 1 Volt at the high-current side. Magnets to be powered by the supplies are made with Nb_3Sn and NbTi wires, operate at 600 and 300 Amps, have inductances of 1.2 and 1.3 Henry and generate magnetic fields of 12 and 7 Tesla, respectively. Both magnets operate at 4 Kelvin and are bath-cooled. So far the power supplies were tested at the operating temperature using a small sc magnet as a load. Expected load curves, while ramping the current of the real magnets, are also discussed. A comparison between these sc supplies and a conventional system based on a room temperature power supply with (high-T_c) current leads is made.**

I. Introduction

A conventional powering system of a low-T_c superconducting magnet consists of a high-current power supply placed at a room temperature and high-current leads into a cryostat. A superconducting power supply enables a conversion between a low alternating and a high direct current of a magnet inside a cryostat. It consists of a low temperature (cold) unit, low- and high- current leads and a control unit placed at a room temperature as depicted in Figure 1.

Within the frame of the INTAS project we developed new advanced sc power supplies to be installed with superconducting magnets in the Ukraine and Russia. The Supply I uses sc repetitive switches, the Supply II employs semiconducting repetitive switches (thyristors) able to operate at low temperatures.

Both powering systems have advantages and disadvantages. Those depend on the operating cycle of a magnet and have been compared in [1].

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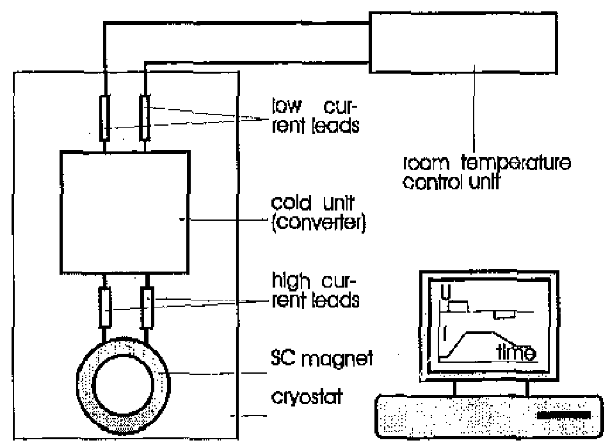

Fig. 1. Schematic view of a superconducting power supply.

II. Principles of Operation

A. Electrical Scheme

The basic scheme of a 50-Hz sc power supply is shown in Figure 2. The terminals of the room temperature unit are connected to the mains represented in the scheme by an e.m.f. $\mathbf{E}_A$ and an impedance $\mathbf{Z}_A$. The unit consists of two switches $\mathbf{S}_A$ and $\mathbf{S}_B$, and a control interface (not shown). Switch $\mathbf{S}_A$ connects and disconnects the device and the mains. Switch $\mathbf{S}_B$ provides a temporary short circuit of the terminals connected to the cold unit to enable recovery of the repetitive switches when running in the inversion mode. The impedance $\mathbf{Z}_B$ limits the current derivative when switch $\mathbf{S}_B$ is in use.

The cold unit enables a conversion between a relatively low alternating current (few Amps) and a relatively high direct current (0.6 kA). The unit consists of a superconducting transformer represented in the figure by primary $\mathbf{L}_P$ and secondary self-inductances $\mathbf{L}_1$ and $\mathbf{L}_2$; two repetitive sc switches $\mathbf{S}_1$ and $\mathbf{S}_2$; and a persistent mode switch $\mathbf{S}_3$ (the inductance of the branch $\mathbf{L}_3$ is also shown). The high-current leads of the unit are connected to a superconducting magnet $\mathbf{L}$.

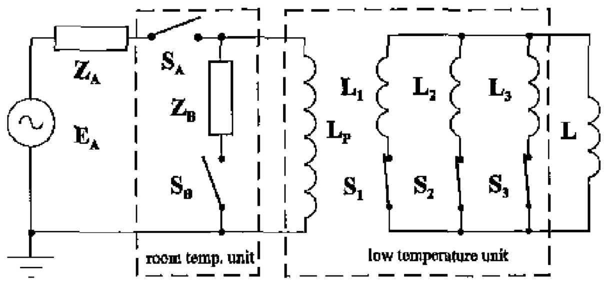

Fig. 2. Electrical scheme of a superconducting converter.

B. Operation of the Device

The operation of the converter with an inductive commutation mode is illustrated in Figure 3. The operation consists of three procedures: *start*, *ramping* and *stop* [2]. The vertical dashed lines indicate points where the voltage of the mains changes its sign. The dotted lines show breaks of the time axis to cut on the diagram the activation and the recovery of the switch S_3, which are relatively slow processes. Within one cycle during the ramping procedure, the operation of the device consists of four stages: 1) opening of the repetitive switch, 2) ramping (up or down), 3) closing the switch, 4) commutation.

C. Theoretical Description

The performance of a low-temperature unit has been well studied theoretically for both superconducting [2] and semi-conducting [4] repetitive switches, different shapes of the primary current and control algorithms [2], [5]. When equipped with sc or semi-conducting repetitive switches, the power supply is able to operate in four or two quadrants, respectively. This is achieved by changing a sequence of control signals.

Input data required to describe the power supplies theoretically are summarised in Table I. The operating frequency is assumed to be constant. The commutation inductance is measured with the switches S_1 and S_2 being closed. The theory applied here has been verified experimentally. The energy efficiency is calculated by summing the losses of the cold unit's components [6]. Dynamic loss of the Supply I (in % to the total loss) comes from: the repetitive switches – 85 %, the persistent mode switch – 9 %, the transformer – 4 %.

III. Design and Construction

A. The Cold Part

Two different power supplies for two magnets, a separator magnet and a research magnet, are developed.

1) The transformer and the repetitive switches: Relevant specifications of the transformers and the switches are listed in Table I, the design is explained in Ref. [3]. A summary of the conductors used for the sc components is presented in Table II. For the sc Supply I a pair of thermally controlled NbTi switches with the reverse current of 5.6 A is used. For the hybrid Supply II, a pair of Si- thyristors of type T210N from EUPEC® is used as the repetitive switches. Each of the thyristors has a forward current of 330 A_{rms} and a voltage drop of 0.8 V at 410 Kelvin and it is able to operate at low temperature. The arrangement of the similar switch unit is explained in [4].

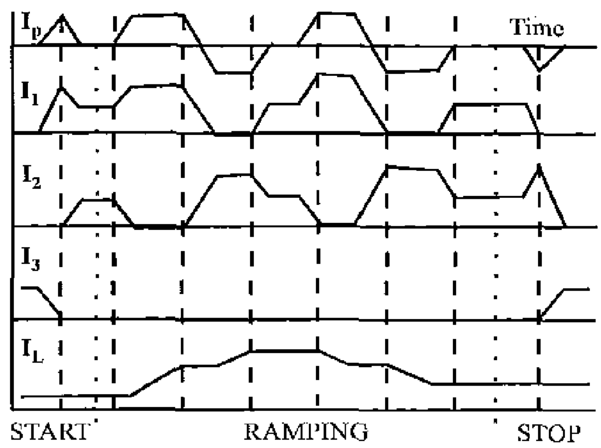

Fig. 3. Branch current diagrams explaining the operation of a sc power supply with an inductive commutation mode. The branches are labeled in Figure 2.

2) The magnets: The separator magnet I is a solenoid with inner, outer diameters and height equal to 128, 260 and 130 mm, respectively. The magnet conductor is a 1.5-mm Nb_3Sn/Cu round wire. The magnet has an inductance of 1.2 H. At the operating current of 615 A, the central induction is 10 T. The magnet is aimed to operate continuously and uses a refrigerator cycle for cooling.

The research magnet II produced in Russia is a solenoid with inner, outer diameters and height equal to 121, 178 and 200 mm, respectively. The magnet conductor is a 1-mm NbTi/Cu round wire wound in 4180 turns. The magnet has an inductance of 1.3 Henry and it is equipped with a persistent mode switch. Resistance of the switch gate made with NbTi/CuNi wire is 10 Ω. At the operating current of 330 A the central induction equals 6.9 T. The magnet is operated from time to time and uses liquid helium (a liquifier cooling cycle). A small model magnet III with an inductance of 10.7 mH was used for testing the power supplies.

TABLE I
Input Data of the Power Supplies

Parameter	Supply I	Supply II
Operating frequency, [Hz]	50	50
Turns ratio of the transformer	145.6	30
Primary voltage, [V]	40 ‹ › 250	220
Primary commutation inductance, [mH]	46	30
Magnet inductance, [H]	1.2	1.3
Repetitive switches $S_{1,2}$:	Supercond.	Semicond.
Reverse current, [A]	5.6	0
Forward voltage, [V]	0	0.8
Recovery time, [ms]	2.5	< 1
Heater resistance, [Ohm]	52	-
Control voltage amplitude, [V]	15	2
Control pulse width, [ms]	0.8	1

TABLE II
SPECIFICATION OF THE CONDUCTORS

Applied in	Material	Bare size, mm	Filaments
Primary coil	NbTi/CuNi	Ø 0.22	574
Secondary coil	Nb_3Sn/Cu	5 × 0.2	tape
Switch gate	NbTi	16 × 0.008	foil

B. Room temperature unit

1) The power unit represented by the switches S_A and S_B in Figure 2, provides a certain shape of the current through the primary coil of the transformer. The unit also amplifies control pulses to all switches.

2) The control. An algorithm that is executed by a personal computer determines the shape of the primary current. The proper sequence of the control signals leads to the required procedure performed by the supply.

C. Efficiency and cooling

1) Steady State Magnet. A continuously operated low-T_c super-conducting magnet usually employs a refrigerator cycle for cooling. A conventional powering system of a magnet employs high-current current leads into a cryostat. An efficiency of a current lead was recently improved by adding high-T_c inserts [7]. In terms of refrigerator power at 4 Kelvin a static loss is reduced from ~ 4 to 0.5 W/kA per a (protected) lead.

A sc supply as the one depicted in Figure 4 eludes the static loss completely. However, when ramping a magnet, a conversion between a low alternating and a high direct current takes place inside a cryostat. A refrigerator removes the associated dynamic loss, which is typically few percent of the magnet energy change. As the static loss is zero, after a sufficient storage time a total loss over the operation cycle becomes equal to or less than that of the conventional system, see Ref. [1]. Typical breakeven time depends on the magnet parameters. For a magnet with an inductance of 1 H and an operating current of 1 kA the breakeven storage time is one hour with the copper leads and several hours with the high-T_c leads.

2) Research magnet. For a typical research magnet operating conditions are rather different. Usually it operates from time to time and it is cooled in a liquifier cycle. This means that an enthalpy of the helium vapour is not utilised in a refrigerator cycle, though it can be used to cool current leads and thermal shields, for instance. This way cuts down the investment costs of a cooling system. However, those are included indirectly into the running costs, which are higher in this case.

A sc power supply uses only liquid helium for cooling and the direct application is not effective in this case. When sc repetitive switches are replaced with semi-conducting ones operating at a room temperature inside a cryostat, the energy efficiency can be increased above 99 % [4]. The most efficient scheme employs additional high-T_c leads to connect the switches with the transformer and the magnet. A standby temperature of the switches is ~ 30 K, and the associated static heat leak via the leads is below 0.1 W/kA.

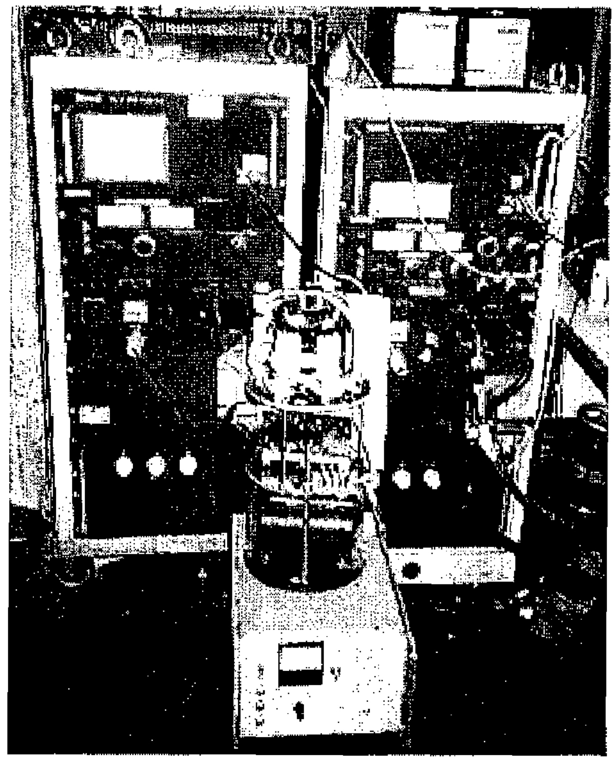

Fig. 4. A completed sc power supply together with the model magnet and the control unit (front) compared to a conventional room temperature power supply (two boxes at the back) for the same magnet current.

Such hybrid power supply utilizes the enthalpy of helium gas to cool the repetitive switches and the leads. A saturated vapor from 1 liter of liquid helium may absorb ~ 170 kJ of energy before its temperature reaches 300 Kelvin. We developed a power supply that is efficient in this environment. Specifications of the Supply II are listed in Table II, details of its arrangement are reported in Ref. [4].

IV. RESULTS AND DISCUSSION

Various experiments and simulations are performed in order to characterise the operation of the power supplies. Expected voltage-current and energy efficiency curves of the supply I connected to the magnet I are shown in Figure 5. As mentioned, the power supply is able to operate in 4 quadrants. For sake of simplicity V-I curve is plotted in one quadrant using the symmetry. At the magnet current equal to 600 A, the stored energy is 216 kJ. The energy lost by the sc power supply per one operating cycle of the magnet is 13 kJ. When compared to a conventional powering system with copper or high-T_c current leads, the breakeven time is equal to 1 or 6 hours respectively. As the magnet operates continuously, the application of the sc power supply is beneficial. Figure 6 presents a typical dependency of the current, voltage and power vs. time when ramping up the magnet current.

When the magnet II is equipped with the hybrid power supply, ramping of the current between 0 and 330 A at 5 Volts

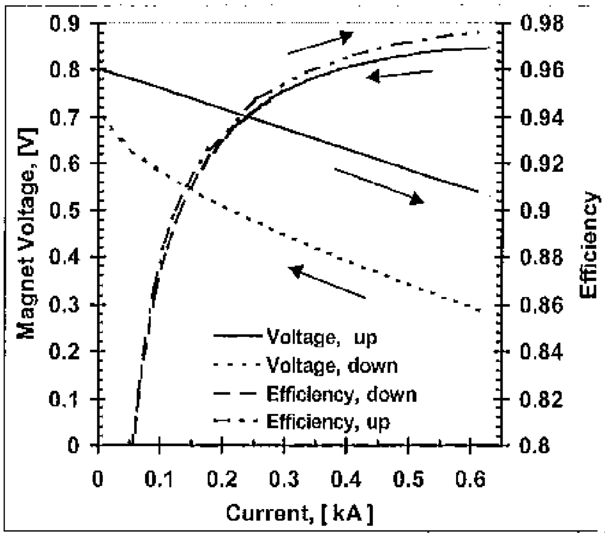

Fig. 5. V-I curves and the energy efficiency of the supply I when ramping the magnet current (calculated at the primary voltage of 130 V_{rms}, the arrows show the direction of the magnet current).

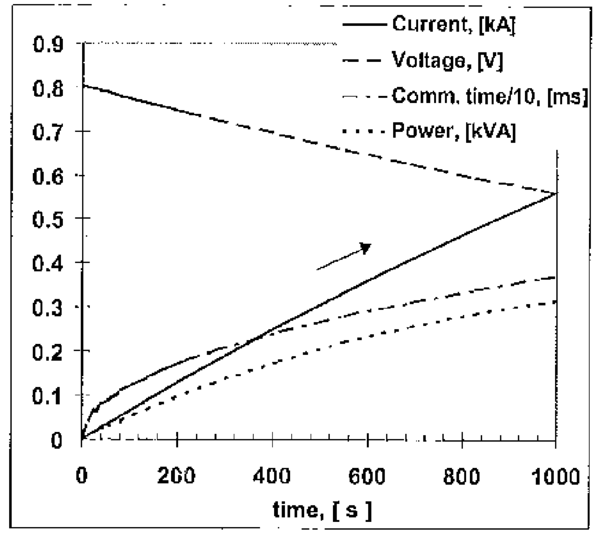

Fig. 6. Magnet current, voltage, and power versus time when powering the magnet I with supply I (calculated at the primary voltage of 130 V_{rms}, see Table I). The commutation time [2] of the power supply is also depicted. It is an important feedback parameter used to perform the inductive commutation.

takes 66 seconds. The liquid helium consumption due to one ramping cycle is 0.4 liters. The standby loss via the vapor-cooled current leads connecting the magnet and the switches gives an additional evaporation of 0.02 liter/hour of liquid helium. The conventional powering system causes an equivalent continuous evaporation of 0.2 liter/hour of liquid helium. In other words, the breakeven operating time with a constant current is two hours.

In the past, a weak protection of sc power supplies was a major technical obstacle to their wider application. Since then, protection methods were greatly improved. Today, a protection system offers a reversible fail-safe operation of a sc power supply [5]. This means that if any component of the supply quenches, it will recover to the superconducting state without a reduction of a magnet current.

V. Conclusions

1. Novel advanced power supplies for low $-T_c$ magnets are developed and studied.
2. When a magnet operates continuously and uses a refrigerator cycle for cooling, a power supply equipped with superconducting repetitive switches is the most efficient.
3. For magnets that are cooled with liquid helium, a hybrid power supply that uses a superconducting transformer and semi-conducting repetitive switches, is an option.

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