A Novel Miniature Superconducting Converter for 1 kA Magnets

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Abstract—**A miniature full-wave converter to control the current of a superconducting magnet is developed and tested in our institutes. Typical design values of the device are: AC voltage of 35 V, current of 7 A, and frequency 50-60 Hz; DC voltage of ± 0.2 V, and current of ± 1 kA. An efficiency is better than 97% and a 'cold' volume is less than 1 litre. The rectification is achieved by means of thermally controlled superconducting switches. The high reliability of the device is ensured by means of a mechanical switch. The device provides an efficient way to a fine control of the magnet current.**

I. INTRODUCTION

When a DC superconducting (SC) magnet is in a persistent mode, there are several causes which may influence the current. Those are: an internal active resistance (conductor and joints), an active or inductive interaction with external objects. The interaction power is rather small (< 100 W).

To control the current in the persistent mode, one can use a small superconducting converter integrated with a magnet. The converter is a device which generates a DC voltage across the magnet. Due to a higher efficiency and a current density, the device has important advantages when compared to the one based on semiconductors [1]. The maximum current of the converter is not a limitation and several recent designs in the range of 0.1 to 100 kA are reviewed [2].

The average power of the converter is proportional to the product of the operating frequency and the primary energy of the transformer [3]. An increase of the operating frequency allows further reduction of the converter mass-volume which is advantageous. The new 50 Hz converter described here demonstrates the benefits of this approach.

II. PRINCIPLES OF OPERATION

A. Electrical Scheme

The particular converter used in our experiments employs a single phase, full-wave scheme with an inductive commutation of the secondary currents as it is shown in Fig. 1.

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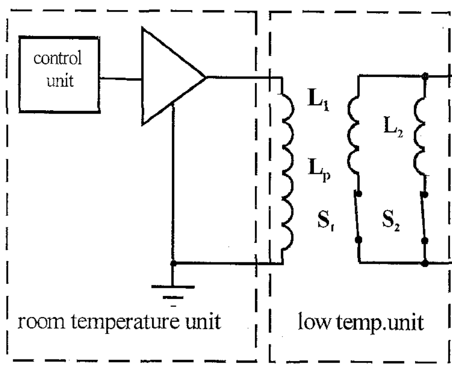

Fig. 1. Schematic view of the converter system.

The power of the device is not high, so one can use an amplifier controlled by a micro-computer to define a certain shape of the primary current [3]. The low temperature (cold) unit enables the conversion between a relatively low AC primary current (few Amps) and a high DC current (1 kA) of the magnet **L**. The unit consists of a centre tapped SC transformer and two repetitive switches $\mathbf{S_1}$ and $\mathbf{S_2}$. The transformer is represented in the figure by the primary $\mathbf{L_p}$ and secondary $\mathbf{L_1}$ and $\mathbf{L_2}$ self-inductances of the coils, while mutual inductances are not shown. The cold mechanical switch $\mathbf{S_3}$ is used to improve the protection (the inductance of the branch L_3~10 μH is also shown). In a standby mode it is opened and does not influence the operation of the converter.

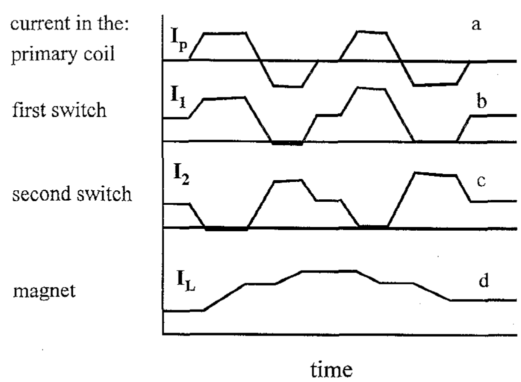

Fig. 2. Diagrams explaining the operation of the converter with the inductive commutation mode.

B. Operation of the Device

A superconducting converter is a bipolar device. It allows to ramp a positive or a negative current of the magnet both up and down. Each option is available by a simple change of the sequence of the control signals. Within one cycle the operation consists of four stages: 1) commutation; 2) opening of the repetitive switch; 3) ramping the current (up or down); 4) closing the switch. As a result, currents in the converter branches are changing as it is shown in Fig. 2.

C. Theory

The performance of a SC converter has been well studied theoretically for different shapes of the primary current and control algorithms [2], [3].

Input data required to describe the converter theoretically are summarised in Table I. The operating frequency is considered constant here. The AC loss and efficiency of the converter were also studied, but a quantitative description requires a knowledge of the loss in the converter components. The results of the analyses will be demonstrated below in comparison with the experiment.

D. Fine control of the magnet current

A higher operating frequency of the device allows the ramping of a smaller portion of the energy in one cycle. Assuming the width of the ramping stage of $t_1 \approx 3$ms and an effective voltage generated across the magnet of

$$U_e = \frac{1}{t_1}\int_0^{t_1} U(t)dt \approx 8\ \mathrm{mV},$$

one can find an elementary change of the magnetic flux

$$\Delta\Phi = \int_0^{t_1} U(t)dt \approx 2.4\times10^{-5}\ \mathrm{V\times s}.$$

For the typical values of the magnet inductance $L = 1$ H and current $I_L = 1$ kA the absolute and the relative current changes in one cycle are respectively:

TABLE I
INPUT DATA OF THE CONVERTER

Parameter	Value
Operating frequency, [Hz]	50
Transformation coefficient	136
Primary voltage amplitude, [V]	5⇔40
Primary commutation inductance, [mH]	2.8
Magnet inductance, [mH]	10.7
Repetitive switches $S_{1,2}$:	
Min. propagation current, [A]	9.6
Recovery time, [ms]	1.5
Heater resistance, [Ohm]	18
Control voltage amplitude, [V]	6
Control pulse width, [ms]	0.8

$$\Delta I_L \approx 24\ \mathrm{mA};\quad \frac{\Delta I_L}{I_L} \approx 2.4\times10^{-6}\ \%.$$

This small change can be easily measured by counting the number of operating cycles. The total uncertainty of the voltage integral is less than 5%.

III. Design and Construction

The requirements that have to be met by the converter are:
- input voltage of 35 V at 50-60 Hz;
- input current below 10 A;
- output current of $\pm$ 1 kA;
- average output voltage $\pm$ 0.2 V;
- energy efficiency better than 97%.
- liquid helium operation temperature,
- cold volume less than 1 litre.

A. The cold part

1) The transformer and the switches A summary of the conductors used to built the converter and the magnet is presented in Table II. The SC transformer and switch characteristics are specified in Tables II and III respectively. The transformer has an iron core of the type 2×SG 54/25 [4]. The primary coil contains 340 turns, each of two secondary coils contain 2.5 turns. The active length of the bifilar folded gate of each switch is 25 mm. The number of normal zones triggered initially by the heater sections in the gate is 12. The similar design (except the size) and technology as described in [4] is used to prepare the components.

The AC connections are made with the same tape conductor as used for the secondary coils. The DC connections are made of the same conductor as the magnet. As the device is small, an architecture similar to the usual printed circuit board is used to place and to connect the components.

2) Other components A small superconducting magnet is used as a temporary load. It has an inductance of 10.7 mH and a DC current of 1.7 kA.

A mechanical switch S_3 [5] is used for the protection. The inductance of the SC control coils is ~0.4 H. With a current of 40 A supplied to the coils, the switch gate resistance is well below 0.5 μΩ at the current of 1 kA. The transition time (from the open to the closed state) can be 20 ms and is

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	26*0.008	foil
Magnet	NbTi/Cu	2.5×1	36

TABLE III
SPECIFICATION OF THE TRANSFORMER

Parameter	Value
Primary coil self-inductance (at 40 Veff) , [H]	2.5
Transformation coefficient	68
Coupling coefficient	>0.99
Primary inductance (both secondary coils are short-circuited), [mH]	2.8
Height of the outer coil, [mm]	36
Outer diameter of the coils, [mm]	40

limited presently by the control voltage.

Two diodes connected in parallel to the converter and placed above the liquid helium level provide a further protection (in case if the switch S_3 fails).

B. Room temperature part

1) The power unit provides a certain shape of the current (voltage) applied to the primary coil of the transformer. It also supplies control pulses to the repetitive and mechanical switches.

It can be seen from Fig. 2, that the operation of the converter requires a diode-like behaviour of the repetitive switches. A switch has to be opened each time when the current of a certain polarity crosses zero.
The scheme shown in Fig. 3 provides this function of the switches and allows to make the converter self-switching. The scheme employs a small saturable core transformer $\mathbf{T}_h$ with a rectangular hysteresis loop and a diode $\mathbf{D}_h$. It has to be attached to each repetitive switch at 4 K. The tape connecting the switch and the 1 kA transformer serves as a primary coil, while a secondary coil is connected to a switch heater $\mathbf{R}_h$ via the diode $\mathbf{D}_h$. Only when a switch current is almost zero, the core is not saturated and the current change during the commutation stage generates a voltage pulse to trigger the switch. The diode selects a proper polarity of the pulse. PSPICE simulations has validated the scheme.

2) The control unit The shape of the primary current is determined by an algorithm that is executed via a control unit. The constant current derivative kept in the primary coil

TABLE IV
SPECIFICATION OF THE REPETITIVE SWITCHES

Parameter	Value
Min. propagation current, [A]	9.6
Max. off resistance, [Ω]	0.1
Gate time constant, [ms]	1
Heater resistance, [Ω]	18
Control voltage, [V]	6
Width of the control pulse, [ms]	0.8
Control pulse frequency, [Hz]	50

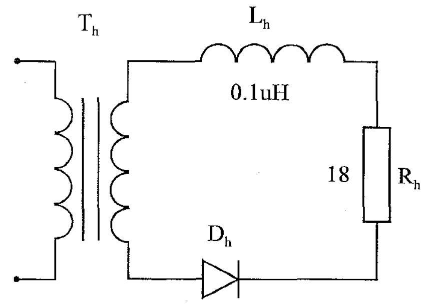

Fig. 3. The control scheme providing a repetitive switch with a diode-like function ($\mathbf{T}_h$ -saturable core transformer, open ends belong to the primary coil; $\mathbf{D}_h$-diode, $\mathbf{R}_h$- resistance of a switch heater, $\mathbf{L}_h$-inductance of the heater).

during each operation stage [3] is used to shape the currents. The control unit consists of a PC and a Keithley-500 measurement and control system. The code is written in PASCAL and has multiple scenarios to control the magnet current.

In the case of a quench in the converter circuits a quench detector generates a signal to close switch S_3. The switch closes for a period of ~0.1 s, which is sufficient to recover the superconducting state.

IV. RESULTS AND DISCUSSION

Various experiments and numerical simulations were performed in order to characterise the converter operation. During the experiments the converter has performed reliably and the design has proven to be fail-safe.

A. Idle Mode

The maximum voltage generated across the opened high current terminals of the converter is 0.25 V. The converter leakage current is 10 A, which is close to the reverse current in the switches.

B. Short Circuit Mode

The measured maximum AC current of the converter is 1200 A and is limited by the quench current of the switches S_1 and S_2. The primary commutation impedance is 0.88 Ω and is determined by the transformer stray inductance, see Table III.

C. Inductive Load

1) External characteristic The output voltage versus the current is presented in Fig. 4 and 5. The primary voltage as a parameter is varied in the range of 5 to 40 V. Four-quadrant operation is available. As the characteristic is symmetric, only a part for a positive current is plotted. The solid lines are measured, while the broken lines are calculated from the theory. Each solid line represents an array of thousands of the experimental points.

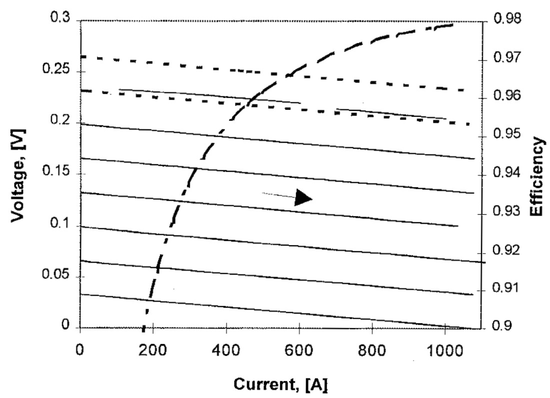

Fig. 4. Output characteristics of the rectifier (the arrow shows the direction of the current change; solid lines are measured, and dashed lines are calculated).

The arrows show the direction of the current change. The efficiency is calculated at 20 V across the primary coil with a scaled loss based on the data of a larger transformer [4] and is shown by dashed lines.

2) Quench Behaviour Fig. 6 demonstrates the experimentally observed operation of the protection system improved by the mechanical switch. In case (3)-when the switch operates, the converter recovers the superconducting state after an artificially induced quench without a dramatic decrease of the magnet current. The current can be kept practically constant (within a few Amps) if to close the switch during 20 ms. This requires a proper control pulse, which can be supplied, for example, by a capacitor based pulse generator.

3) Cost Estimate Our analysis proves, that the total cost **C**, [k$] of a powering system for a magnet (room temperature power supply + copper current leads + refrigerator) can be described as a function of the magnet current **I**, [kA] by $\mathbf{C} = \mathbf{100} \times \mathbf{I}^{0.8}$, valid in the range 0.1 kA $\leq \mathbf{I} \leq$ 25 kA [6]. The material costs of a SC converter are linked mainly to a power and are less dependent on the current. The estimate shows much lower production cost for the converter described here.

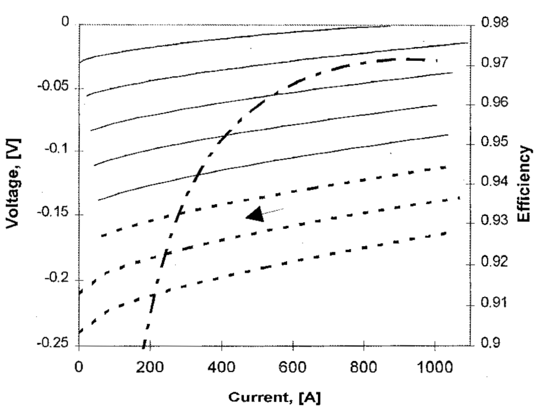

Fig. 5. Output characteristics of the inverter (the arrow shows the direction of the current change; solid lines are measured, and dashed lines are calculated).

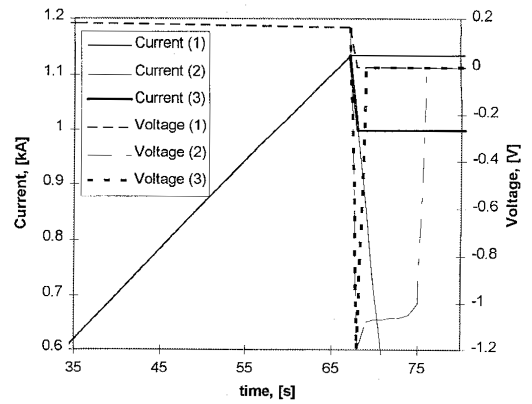

Fig. 6. Magnet current and voltage versus time: (1)-normal operation; (2)-a quench of the converter with the mechanical switch "off"; (3)-the same as (2), with the mechanical switch activated.

V. Conclusions

1. A medium power SC converter is developed and tested. The device is small and inexpensive. It shows an excellent ability to control a magnet current of 1 kA in the persistent mode and can be recommended as a prototype for various applications to stabilise currents in SC circuits.

2. The reliability of the device operation is greatly improved with a novel mechanical protection switch. After a quench the converter recovers the superconducting state without a drastic decrease of the magnet current.

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