Development of a 1 kA, 50 Hz Superconducting Converter

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***Abstract*—A single-phase, thermally switched superconducting converter operating at the mains frequency is being developed and tested in our institutes. Typical design values of the device are: input voltage of 220 V, input current of 7 A; output voltage of 1 V, and current of 1 kA. The average output power is about 750 VA, with an efficiency better than 96%. Test results of the full scale converter while ramping up and down superconducting magnet and a comparison with the theory are presented. The converter will be installed as a part of a power supply system controlling the current of a separator magnet located in Ukraine for an iron ore recycling process.**

I. INTRODUCTION

An AC/DC superconducting converter allows both the rectification of an AC current (voltage) and the inversion of a DC current (voltage). It serves as a compatibility device in between the mains and the magnet. Usually, the converter consists of a low temperature (cold) unit, a room temperature power unit, and control part (also placed at room temperature) as shown in Fig. 1. The cold unit is connected via high-current leads, made of low or high T_c material, to the magnet and via low-current leads to the room temperature unit. Due to the energy conversion at low temperatures, there is an additional heat load for the cryogenic system. However, in this design the high current leads connecting low and room temperature areas are absent. Depending on the operating conditions, this can result in a lower total heat load [1].

The main reasons for developing the converter for a separator magnet, some important design features of the device, as well as the principles and the theory of operation are published elsewhere [1]-[3]. The experimental investigation of the different rectifier components is completed [4]. This paper presents results of the experimental investigation and characterisation of the converter while ramping the current of an inductive load and gives a comparison with the theory.

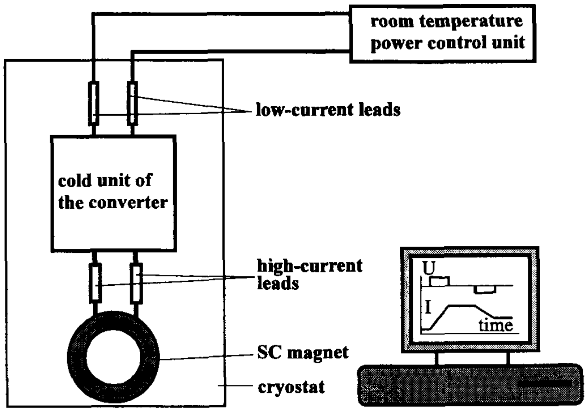

Fig. 1. A schematic view of the converter system.

II. PRINCIPLES OF OPERATION

A sketch of the experimental setup used for our measurements is presented in Fig. 1. The converter cold unit includes a superconducting transformer, switches, protection circuits, sensors, and the cooling system. The room tempera-ture power unit conditions the power to make the mains and the cold unit compatible. It also supplies the control pulses to the superconducting switches. The controls are PC-based and contain a control system, a code and a user shell. They control the operation of the cold and the room temperature power units and support the user interface.

A. Electrical Scheme

The basic electrical scheme of the converter is shown in Fig. 2. The terminals of the room temperature power unit are connected to the mains which is represented in the scheme by an e.m.f. $\mathbf{E}_A$ and an impedance $\mathbf{Z}_A$. The unit consists of two semiconducting switches $\mathbf{S}_A$ and $\mathbf{S}_B$, , and a control interface. Switch $\mathbf{S}_A$ serves to connect and to disconnect the device and the mains, switch $\mathbf{S}_B$ provides a temporary short circuit of the terminals connected to the cold unit in order to enable recovery of the repetitive switches when running in the inver-

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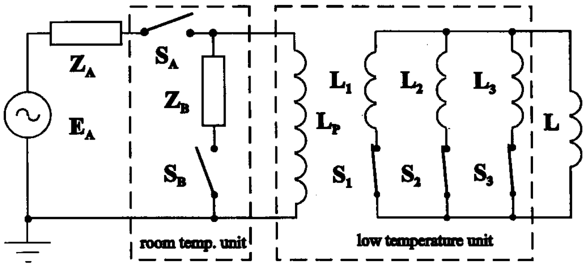

Fig. 2. The electrical scheme of the superconducting converter.

sion mode. The branch impedance Z_B limits the current derivative when switch S_B is in use. The cold unit enables the conversion between a relatively low AC current (few Amps) and a relatively high DC current (1 kA). It consists of a superconducting transformer represented in the figure by a primary L_P and secondary self-inductances L_1 and L_2; two repetitive superconducting switches S_1 and S_2; and a persistent mode switch S_3 (the inductance L_3 of the branch is also shown). The terminals of the unit are connected to the superconducting magnet **L**. The mutual inductances, protection, control and measuring circuits are not shown.

B. Operation of the Device

The operation of the converter with an inductive commutation mode is illustrated in Fig. 3. More details are given in [3]. The operation consists of several procedures: *start*, *ramping and stop*. The dashed lines indicate points where the mains voltage changes a sign. The dotted lines show breaks of the time axis caused by the activation and 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. The commutation time (which is the time required to commutate the magnet current between two converter branches) is an important feedback parameter to control the device in the inductive commutation mode.

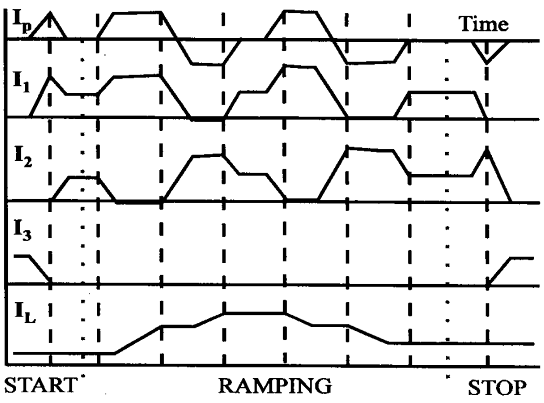

Fig. 3. Diagrams explaining the operation of the converter with the inductive commutation mode.

III. DESIGN AND CONSTRUCTION

The requirements that have to be met by the converter are:
- input voltage (of sinusoidal shape) of 220 V at 50 Hz;
- input current below 8 A;
- four-quadrant operation;
- output current of 1 kA;
- average output voltage up to 1 V;
- energy efficiency better than 96%.
- liquid helium operation temperature.

A. The cold part

1) The transformer and the switches: A summary of the superconducting transformer and switch characteristics is given in Tables I and II respectively. More details are reported in [4]. The interconnections between the different components are made with the same tape conductor as used for the secondary coils. In our previous experiments [5] a separate inductance in the branch **A** of Fig. 2, was used to adjust for the commutation time and the recovery time of the switches. In this converter the inductance is included in the transformer.

2) The protection system: The gates of both repetitive superconducting switches are individually protected by Schottky diode units placed above liquid helium level. The diodes limit the voltage across the switch gate and stabilise

TABLE I
SPECIFICATION OF THE TRANSFORMER

Transformer Parameter	Value
Primary coil self-inductance (at 110 Veff), [H]	80
Transformation coefficient	72.81
Coupling coefficient	0.9997
Primary inductance (both secondary coils are short-circuited), [H]	0.045

TABLE II
SPECIFICATION OF THE SWITCHES

Switch Parameter	S_1	S_2	S_3
Min. propagation current, [A]	9.5	9.4	1
Max. off resistance, [Ω]	0.4	0.4	1.4
Gate time constant, [ms]	1	1.1	2000
Heater resistance, [Ω]	54	58	20
Control voltage, [V]	16	17	6
Width of the control pulse, [ms]	0.6	0.6	5
Control pulse frequency, [Hz]	50	50	100

its operation. The high current terminals of the converter are protected by silicon diodes placed above liquid helium level. The low current terminals of the converter are protected against voltage spikes by the varistors placed at the room temperature. Both switches S_A and S_B are protected against overcurrents.

3) The magnets: The separator magnet with an inductance of a few Henry is not yet available for the test. A small superconducting magnet is used in the measurements as a temporary load. It has an inductance of 10.7 mH and a DC current of 1.7 kA.

B. The room temperature part

1) The power unit: The cold unit operates at the mains frequency. This makes the room temperature unit especially simple [3]. In order to limit the current derivative in the branch **B** while ramping down, the copper inductance of 8 mH is used. The control pulse amplitude for the switches S_1-S_3 is specified by the device and can vary between 0 and 40 V, while the width of the pulses is specified by the control unit. For the testing purposes the mains voltage is varied by an auto transformer.

2) The control unit: The control unit consists of a PC and a Keithley-500 measurement and control system using 2 analog, 2 digital inputs and 9 digital outputs. The analog inputs provide the information about the magnet current and the liquid helium level. The digital input gives the sign of the main's voltage. Three digital outputs control the state of the superconducting switches, and two control the semiconducting switches of the power unit. Other channels provide a service information between the PC and the power unit.

In terms of the control code, the operation of the converter is characterised by 17 typed constants, such as scaling factors; target, max., min. values of the load current; max. converter current possible; value of the leakage current; widths of control pulses, activation and recovery times for SC switches, commutation time, etc. The control code is written in PASCAL and has multiple scenario's to control the magnet current (as it is shown, for example, in Fig. 1 on the PC display).

IV. RESULTS AND DISCUSSION

Various experiments and numerical simulations were performed in order to characterise the stages, procedures and modes of 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 by the high current output of the converter is limited at present by the protection of the switches S_1 and S_2 and is 1.07 V in amplitude. 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 1100 A and obviously it is limited by the switches S_1 and S_2. The commutation impedance is 2.7 mΩ and is mainly determined by the transformer stray inductance, see Tables I and II for a comparison.

C. *Inductive Load*

An inductance of the magnet we used is about two orders smaller, than of the separator magnet. This causes higher ramping rate of the magnet current during the tests. According to the theory [5], the same current change in the separator magnet will require about 100 times longer operation of the converter.

1) External characteristic: The average output voltage (over one cycle) versus the current is presented in Fig. 4. Four-quadrant operation is possible with this converter (both positive or negative voltages and currents can be provided by changing the software only). As the characteristic is symmetric, only one part of it (for the positive current) is plotted.
The points are measured, while the lines are calculated. Both solid and broken lines are calculated using the theory given in [3] and assuming that one or two switches are connected in series and the maximum current possible is 1565 A and 3130 A respectively. Arrows show the direction of the magnet current. No problems are expected when connecting two or more switches in series (in fact, one switch section consists of a number of elementary switches connected in series [2], [4]). When the idle voltage is less than 0.42 V, the maximum current of the converter is less than 1000 A

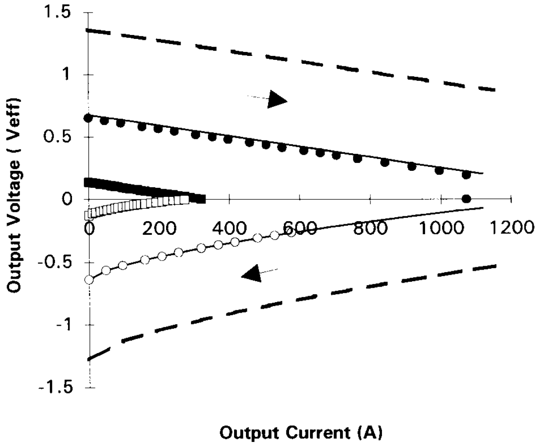

Fig. 4. External characteristic of the converter (arrows show the direction of the magnet current; points are measured, and lines are calculated).

and a reduction of the commutation inductance is required. When the idle voltage is below 0.2 V, the opera-tion of the converter can be improved by using only a part of the elementary switches within each switch section.

Ramping Up (rectification mode): The slope of the characteristics is determined mainly by the commutation impedance. It is adjusted to the switch recovery and can be changed only within a certain range. During the ramping up the leakage currents of the switches $\mathbf{S}_1$ and $\mathbf{S}_2$ increase the primary current amplitude. The maximum current in this mode is 1070 A.

Ramping Down (inversion mode): The slope of the characteristics is changed due to the recovery time of the switches (which is the time required to recover a switch gate from the normal to the superconducting state; 1.6 ms). Practically the same behaviour as we reported in [3] is observed experimentally while pumping down the magnets. The leakage currents of the switches decrease the primary current amplitude during the ramping down.

2) Losses: Losses during the converter operation were measured calorimetrically as a function of the magnet current and result in a consumption of 16 litres of liquid helium per 1 MJ of energy stored in the magnet. The main contributions estimated are as follows: the switches $\mathbf{S}_1$ and $\mathbf{S}_2$ 60%; the switch $\mathbf{S}_3$ 18%; the transformer 18%.

3) Commutation time: A new method to determine the commutation time was tested. The method uses the primary current amplitude measured during the ramping stage by means of a Rogowsky coil (placed at room temperature in the branch **P** of Fig. 2). Due to the iron core transformer used, the amplitude of the primary current is proportional to the magnet current. Only small corrections to account for the switch leakage and the transformer magnetisation currents are required in order to calculate the magnet current and to find the commutation time.

4) Comparison of methods to determine the commutation time: Three methods are compared, see Fig. 2 for the details:
1). Using the magnet current measured by the sensor (as for example, a Hall probe) installed on the magnet **L**. This method is commonly used.
2). Using the currents in the secondary branches **1** and **2** measured by means of Rogowsky coils [5].

3). Using the primary current measured in the branch **P** by the room temperature sensor (such as Rogowsky coil, DCCT or shunt) -as proposed in this paper.

TABLE III
COMPARISON OF METHODS TO DETERMINE THE COMMUTATION TIME

↓ Property | Method →	1-st	2-nd	3-rd
High signal/noise ratio of the sensor	-	+	+
Simple equipment	-	+	+
Easy to access the sensor	-	-	+
The method is self-supported	+	-/+	-/+
Commutation error is not sensitive to the stray magnetic fields	-	+	-

Both the 2-nd and the 3-rd methods strictly saying, need an extra sensor to measure the DC component of the current. Two options are successfully tested to avoid this: 1) manual input of the initial value of the magnet current (the information is restored from the previous operation cycle and is only checked by the user); 2) resistive commutation during the first cycle of the operation (so, permanently a zero initial value of the magnet current is used). The three methods are evaluated and the result is shown in Table III. Both the 1-st and the 3-rd methods (after proper tuning) provide perfect operation of the converter, free of commutation errors. Finally, the 3-rd method is found to be the best for this application.

V. CONCLUSIONS

1. A new 1 kA, 50 Hz superconducting converter is developed and successfully tested in our institutes. It will be applied as the part of the power supply system to control the current of the separator magnet located in the Ukraine [6].

2. The converter provides a four-quadrant operation with a reasonable efficiency. The output voltage will be increased by adding repetitive switches in series.

3. The operation of the converter in the inductive commutation mode is driven by the mains voltage and the primary current. The developed PC-based control system provides a simple and friendly user interface.

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