

Switching Properties of Liquid Nitrogen Cooled IGBTs and 24 kA Demonstration of Current Multiplier by Inductive Storage

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Abstract. We had been developing a current multiplier by inductive storage (CMIS). The CMIS consists of 24 storage copper coils, which soaked into the liquid nitrogen, demonstrates a 24 kA of output current and the continuous current pulses of 3 pulses per second. Switching performance of the IGBTs and diode were tested in the liquid nitrogen bath. These experimental data were used to design the mega-ampere class CMIS. The system consists of the superconductive magnet section with a temperature of 20 K and the IGBT control switch section with a temperature of 77 K.

1. Introduction

The critical problem in a development of the inductive pulsed-power supply is in the opening switch to commutate a large current. This opening switch is required to commutate the current of several mega-amperes for the application to an electro-magnetic launcher. To reduce the duty of switch, the parallel operations of the inductive storages had been done [1, 2]. However, the current magnitude for each opening switch was still large because of the parallel operations of only several inductive storages.

For above solution, we have been developing the inductive pulsed power supply consisting of many coils. This inductive pulsed-power supply is excited in the series connection of each coil and discharged in the parallel connection to obtain the pulsed large electric current. The preliminary experiment showed that this process was correct [3-5].

In this paper, the preliminary experiments of CMIS with 24 inductors have been done. These inductors can be cooled down by liquid nitrogen (L-N₂) to decrease the resistance of the coils and bus-bar. Switching performance of the insulated-gate bipolar transistor (IGBT) and diode were tested in the liquid nitrogen bath. The conceptual design of mega-ampere CMIS and long pulse CMIS were also describes in this paper.

2. 24 kA CMIS performance via copper coil at 77 K

2.1. Principle of CMIS circuit

Figure 1 illustrates the electrical circuit of the SC CMIS. Start-up and termination of the output current are formed by the on and off control of the series IGBTs and parallel IGBTs. Energizing of the SC magnet starts by turning on all series IGBTs. When the parallel IGBTs P₁ turns on and series IGBTs



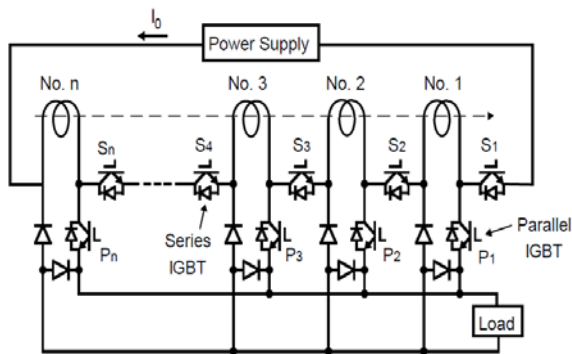


Figure 1. Circuit connection of the CMIS.

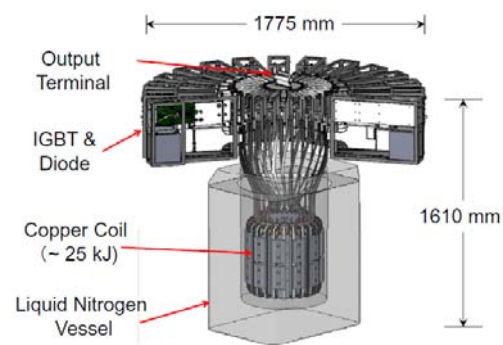


Figure 2 Schematic drawing of 24 kA CMIS .

S_1 turns off coil current I_0 is commutated to the Load. When P_2 is on and S_2 is off, current of No.1 coil and current of No.2 to No. n are commutated to the Load. In case of P_1 to P_n are off and S_1 to S_n are on, the all of module coil current flow into the load, and load current of nI_0 can be obtained. On the other hand, S_1 to S_n turn on and P_1 to P_n turn off, all module coil currents are commutated to the power supply.

2.2. Experimental apparatus 24 kA CMIS

The schematic of experimental apparatus is shown in Fig. 2. It has 24 inductors which form a toroidal coil. The inductance of the toroidal coil in parallel connection is $55 \mu\text{H}$, and stored energy is about 25 kJ. An L- N_2 cooler was used to cool down the inductors until the temperature of L- N_2 . The L- N_2 cooler cools only the toroidal coil, and the lead wire connecting to inductors cannot be cooled in whole. Thus the 24 lead wires were led out the cooler, and connected to IGBTs on the bench for the control devices. For the power supplies to energize the inductors, a 16 volts dc power supply with electric double layer capacitor is used.

2.3. Characteristics of the CMIS

As shown in Fig. 3, an output current of 24 kA was obtained, when the toroidal coil of serial connection was charged up to 1 kA. Decay time constant of the output current was about 70 msec. Equivalent resistance of the output circuit including switching device and coils was about $790 \mu\Omega$.

Continuous current pulse test was conducted with a time interval of 0.3 sec. Each pulse width was adjusted to 50 msec. Typical waveforms of continuous pulses are CMIS is shown in Fig. 4. Pulse heights of output current decreased about 10 % respectively. This was the cause of the large impedance of the electric double layer capacitor which was used in the power supply for charging the serial coils.

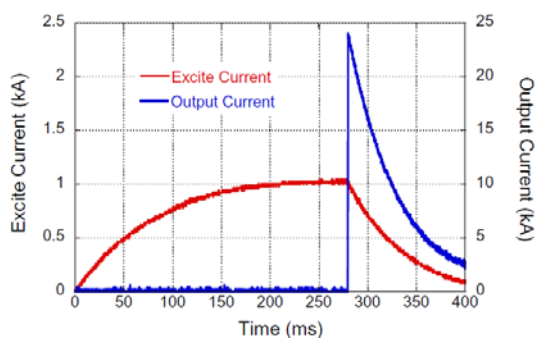


Figure 3. Current waveforms of CMIS.

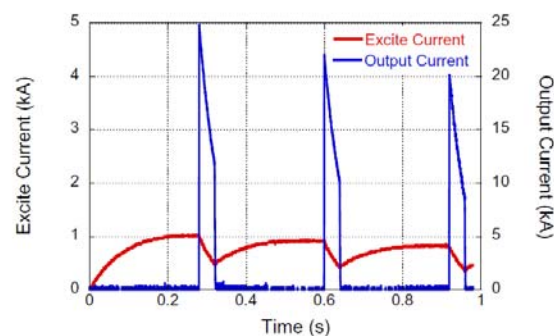


Figure 4 Continuous current pulses in CMIS.

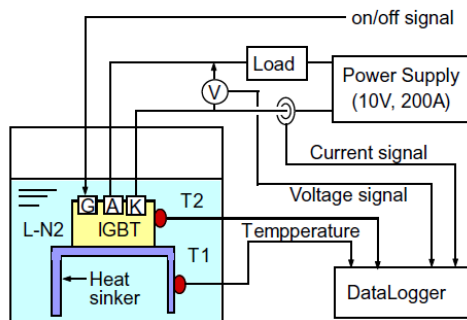


Figure 5. Test-bed for testing IGBTs.

Table 1. Parameters of tested switching device.

Type	Specification
SKM200GB176D (IGBT + IGBT)	V_{CE} : 1.7 kV,
	I_C : 200 A,
	P_C : 500 W
	T_J : -40 ~ 150 °C
PCHMB100B12A (IGBT + Diode)	V_{CE} : 1.2 kV,
	I_{op} : 100 A,
	P_C : 500 W
	T_J : -40 ~ 150 °C

3. Switching characteristics of IGBT and diode in the liquid nitrogen

3.1. Experimental set-up

The merit of using superconducting (SC) coil and SC bus-bar are to realize, 1) low energy consumption for long pulse operation, and 2) high current density and high magnetic field for downsizing the system. To decrease the number of the current leads and to suppress the heat load into the cryostat, the switching device should also be soaked into L-N₂. On the basis of this idea, they were tested in the L-N₂. Test circuit is shown in Fig. 5, and the parameters of test sample are listed in Table1. These samples were used in a prototype CMIS [4, 5].

3.2. Test results

The result of the IGBT cooled by L-N₂ is shown in Fig. 6. When temperature goes down to 77 K, Voltage drop of the IGBT increases. Voltage drop at 300 K and 77 K with zero current were 0.5 V and 1.2 V, respectively. Voltage waveform was non-linear in comparison with the current waveform, but maximum voltage drop did not exceed 2.6 V. When Joule heat occurs at the junction plane, temperature its will go up from 77 K. Increase of the temperature may leads to decrease of the voltage drop, even if the rated current is 100 A.

The result of diode test cooled by L-N₂ is shown in Fig. 6. Voltage drop at 300 K and 77 K with zero current were 0.5 V and 1.1 V, respectively. Non-linearity between voltage drop and current were smaller than that of IGBT. The maximum voltage drop was kept to around 1.5 V.

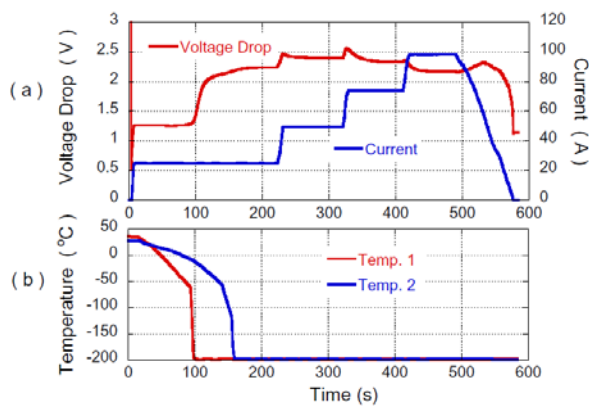


Figure 6. Time evolution of voltage, current (a), and temperature (b) of the IGBT.

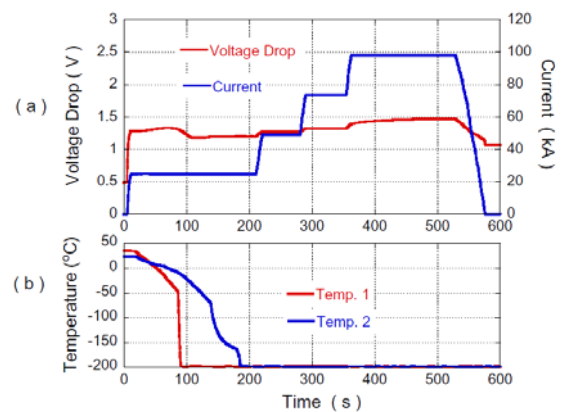


Figure 7. Time evolution of voltage, current (a), and temperature (b) of the diode.

Table 2. Parameters of SC CMIS and calculated results of output currents.

Objective	Mega Ampere CMIS	Long-pulse CMIS
Major radius / Minor radius	1.15 m / 0.45 m	1.15 m / 0.45 m
Number of module coils / turns of a coil	360 / 20	72 / 100
Inductance of Toroidal coil	4.99 H	4.99 H
Magnetic field / Stored energy	3.51 T / 19.6 MJ	3.51 T / 19.6 MJ
Output current / Exciting current	1 MA / 2.8 kA	100 kA / 2.8 kA

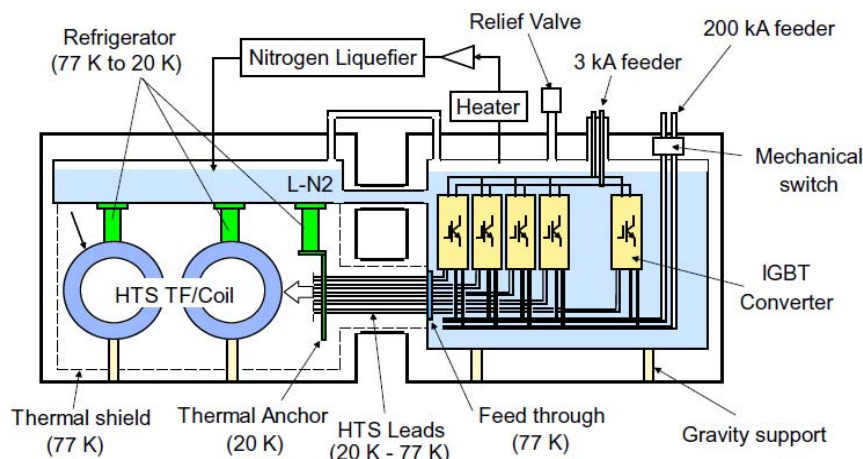


Figure 8. Schematic drawing of high temperature superconducting CMIS.

4. Conceptual design of MA CMIS by SC coils

Figure 8 shows a schematic drawing of the SC CMIS [5]. It consists of the SC module coils and the IGBT control switch. An SC coil is made of multi-filamentary BISCCO tape. The 360 module coils generate the current pulse of 1 MA. Since a decay time constant of the load current is 8.56 s, the pulse duration that the load current decayed to 80 % is 1.7 ms. To increase the pulse duration, repetition of current regulation is applied at the current decay phase. An energy stored coil consists of 72 module coils, and turn number of each coil is 100. Thirty-six modules were used for the current rise, and other 32 modules were used to compensate the current decay. In this way, duration of current flat-top increased to more than 0.1 s. Parameters of MA CMIS and long-pulse CMIS are listed in Table 2.

5. Conclusion

We proposed that new type of the current multiplier by the inductive storage (CMIS). The results are as follows: (1) A prototype CMIS consists of 24 copper coils. Output current of 24 kA was obtained, when the module coils charged up to 1 kA. (2) Current carrying performance of the IGBT and diode were tested in the liquid nitrogen. Voltage drop of the IGBT and diode were less than 3 volt and around 1.5 V, respectively. (3) Two types of large current multipliers by HTS SMES were designed conceptually. One is MA CMIS and the other is long-pulse CMIS. (4) It was confirmed that SC CMIS is effective to reduce a required space and to be flexible in operation.

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