DEVELOPMENT OF A NEW PULSED POWER SUPPLY WITH THE SiC-MOSFET*

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Abstract

A new power supply has been developed using linear transformer driver (LTD) technology that adopts SiC-MOSFETs and capacitors without a thyratron switch or a pulse forming network (PFN) device. A new power supply was also designed by connecting the SiC-MOSFETs and the LTD modules in parallel-series. The output voltage and current were 40 kV and 4 kA, respectively with a pulse width of 1500 nsec at a repetition rate of 25 Hz. Furthermore, by adjusting the correction module, to an output voltage per stage of 1/1000, a resolution of the voltage correction of ±0.1 % could be achieved. It was possible to output the current with arbitrary timing by using a trigger input for each LTD module. As a result, fine adjustment of the output voltage waveform was possible within the order of nanoseconds.

This new power supply with high voltage output, current output, and very fast pulse operation is one of the most important key technologies for a kicker system using SiC-MOSFETs. The design and preliminary test results of this prototype power supply are presented here.

INTRODUCTION

A new switch device is required for an ultra-high-speed short pulse power supply to replace the thyratron switch, because its lifetime is difficult to evaluate. This is especially true in the case of the 3-GeV rapid-cycling synchrotron (RCS) [1] located in the Japan Proton Accelerator Research Complex (J-PARC) [2], where 8 twin-type kicker power supplies [3] and 16 thyratron switches are currently used. At the moment, to maintain the accelerator in continuous and stable operation it is necessary to constantly have many thyratron switch spare parts on hand, which is very costly. In addition, the production of thyratron switches may be discontinued because it is a discharge tube.

The R&D study on a new switching device using a semi-conductor switch with a longer lifetime was initiated. Based on the LTD scheme [4], a new LTD layout was developed that adopted the parallel and series connections of the SiC-MOSFETs with small losses at high speed switching. In addition, this new LTD module is not limited to the usage as only switching devices. It can be used as a new pulsed power supply for the RCS kicker power supply by mounting large-capacity capacitors.

OVER VIEW OF THE NEW LTD MODULE

Basic Specifications of the New Power Supply

The basic design specification of the new RCS kicker power supply using the new LTD modules is shown in Table 1. Because a conventional PFN circuit is not used, the rated output voltage is only half of the currently required RCS kicker power supply.

Table 1: New RCS Kicker Power Supply Specifications

Contents	Specifications
Max output voltage	40 kV
Max output current	4 kA
Withstand voltage for reflected wave	±40 kV
Pulse width of the output waveform	1500 ns
Rise time of the rectangular wave	Under 250 ns
Repetition frequency	25 Hz

Basic Specifications of the New LTD Module

The new module scheme adopted a LTD capacitor discharge method. In particular, the SiC-MOSFET used an N-channel Silicon Carbide Power MOSFET. The characteristics of the SiC-MOSFET are shown in Table 2.

Table 2: SiC-MOSFET Specifications

Contents	Specifications
V_{DSS}	1200 V
$R_{DS(on)}$(Typ.)	30 mΩ
I_D	72 A
P_D	339 W

Two types of LTD modules were designed: the main LTD module, forming the main output waveform; and the correction LTD module, performing the droop correction for the flattop waveform.

The basic circuit layout of the main LTD module and the picture are shown in Figs. 1 and 2, respectively. The board size was 400 mm wide by 430 mm long. In the main LTD module, two SiC-MOSFETs were connected in series to one switch circuit, and the maximum voltage derating per main LTD module was set to 800 V. The pulse current per SiC-MOSFET was 180 A due to the pulse width of the output waveform was 1500 ns and the repetition rate was 25 Hz. Therefore, by setting 15 parallel main circuits per module it was possible to achieve the rated output of 2 kA.

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Also, to use it as a RCS kicker power supply, it was necessary to provide an absorption circuit which had the same function as an end clipper device. The absorbing circuit absorbed both the reflected wave and the beam induced voltage from the kicker magnet [5]. For the absorption circuit, the SiC-MOSFET was normally turned on, and the induced voltage was consumed by the resistance of the absorption circuit. Immediately before the switch circuit SiC-MOSFETs were turned on, the absorption circuit SiC-MOSFET was turned off; after output, the absorption circuit SiC-MOSFET was turned on again.

The new LTD module has 50 stages connected in series, and these system boards are connected in parallel, creating a new pulse power supply with a 40 kV/4 kA output performance. This is consistent with one of the current twin-type RCS kicker power supplies. Furthermore, to compensate for ±0.1 % of the 40 kV output waveform, a 40 V output correction LTD module was used which can be triggered with arbitrary timing. By connecting 20 correction LTD modules in series and setting the trigger input time of each module, it was possible to compensate for ±1 % of the output voltage waveform with ±0.1 % resolution. An optical trigger signal was used for the SiC-MOSFETs gate signal.

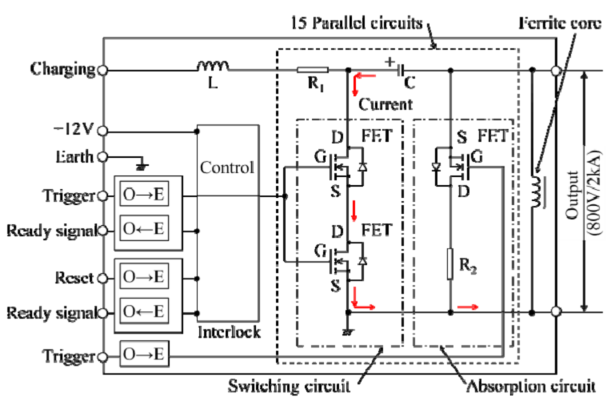

Figure 1: Basic circuit of the new main LTD module.

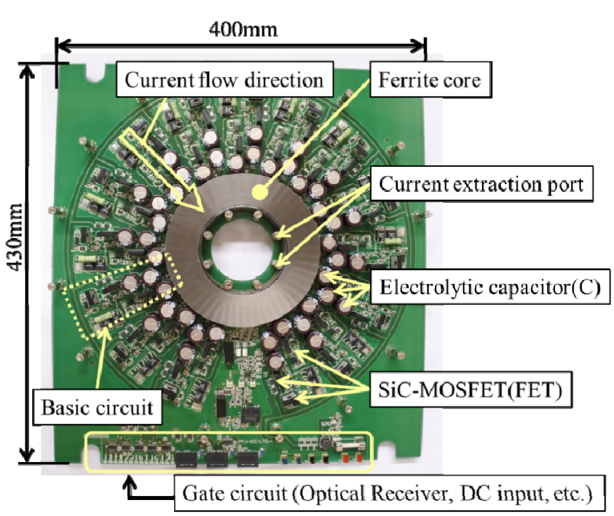

Figure 2: Picture of the new main LTD modules.

MEASUREMENT RESULTS

Main LTD Circuit Module

The output voltage waveform was measured using one main LTD module at a charging voltage of 800 V and a trigger ON-time of 1500 nsec. The output load resistance was 0.4 Ω and the output current was 2 kA. The result was a rectangular wave voltage with a rise time of 120 ns; a pulse width of 1500 nsec; a flat top droop of 40 V; and a peak value of 800 V (Fig. 3).

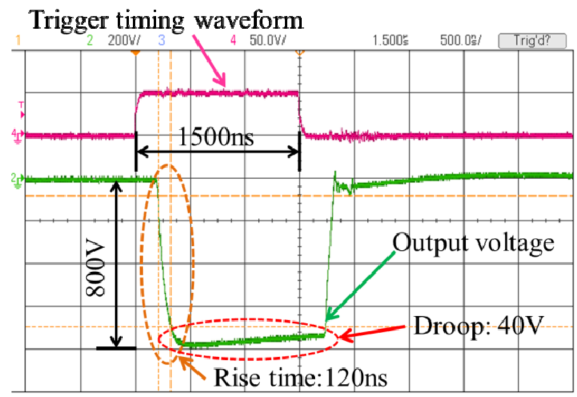

Figure 3: Measurement result of the output voltage waveform at one main LTD module.

Prototype Power Supply

The prototype power supply consisted of 5 main LTD modules and 4 correction LTD modules connected in series. The output voltage waveforms were measured both when only the 5 main LTD modules were operated and when the droop correction was active at the flat top using the 4 correction LTD modules. The measurement conditions were as follows: the trigger ON-times of the 5 main LTD modules were 1500 ns of each other; and when 4 correction LTD modules were shifted from the main LTD module by 300 ns of each other. The DC charge voltage of the main LTD module was 800 V and the correction LTD module was 40 V; the external resistive load was 5 Ω. The SiC-MOSFETs of the absorption circuit were always off.

The measurement results are shown in Figs. 4 and 5. The peak voltage of the output waveform of 3.8 kV and the 200 V droop (5 %) is shown in Fig. 4. The flat top was compensated within ±4 V (±0.1 %) by the correction LTD modules as shown in Fig. 5. The rise-time of the output voltage waveform was 100 ns or less. This performance is sufficient to function as a RCS kicker power supply. In the future, the reason for not reaching 4 kV will be investigated.

Absorption Circuit

Performance evaluation of the absorption circuit was carried out using one main module. In the test, an AC voltage of 10 V/550 Hz, simulating the beam induced voltage was applied between the output terminals as shown in Fig. 1. At this time, a resistor of 10 Ω was additionally connected between the output terminal and the

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AC power supply. Then, in the absorption circuit, when the SiC-MOSFET was switched off and on, the terminal voltage between the SiC-MOSFET and the resistor R_2 (6 Ω) was measured, as shown in Figs. 6 and 7, respectively. The terminal voltage at switch on was sufficiently small compared to the voltage at switch off. The voltage at switch on was due to the added 10 Ω resistor and the resistor R_2 of the absorption circuit. It was confirmed that the on resistance of the SiC-MOSFET was very small and it was possible to effectively absorb the induced voltage. From these results (Figs. 4 and 5), it was also confirmed that the absorption circuit does not affect the output waveform even when the main switch circuit is turned on to output.

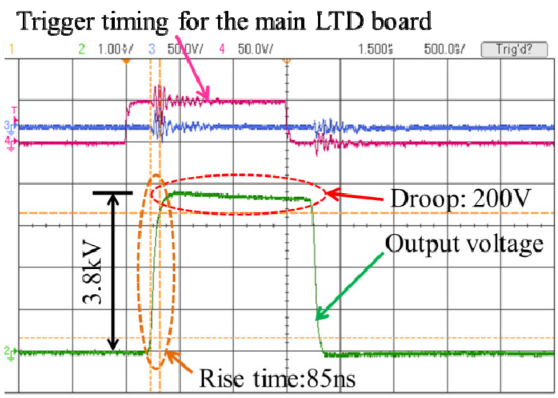

Figure 4: Measurement result of the prototype power supply when only the main circuits were operated.

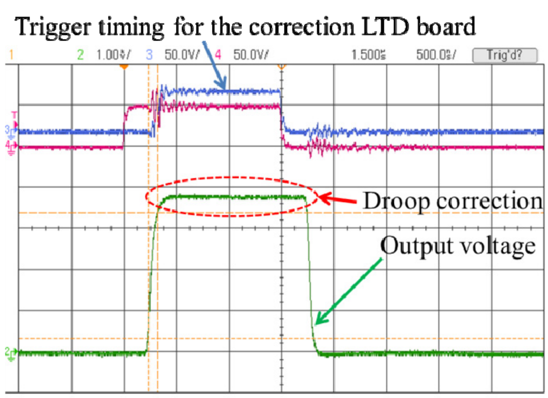

Figure 5: Measurement result of the prototype power supply when the flat top corrections were active.

CONCLUSION

A new switching device using SiC-MOSFETs has been designed. As a development type, the new LTD module was designed with an absorption circuit that can be used as a RCS kicker power supply. Since this module does not have a PFN device, the rated voltage can be halved, and a very compact power supply can be manufactured for it. Preliminary testing has indicated that the rise-time and flat top accuracy performance are sufficient to confirm that it can be used as a RCS kicker power supply.

In the future, main and correction modules will be added to enable an output of 20 kV, which can operate in the atmosphere. Furthermore, it will be connected to a kicker magnet and tested to demonstrate its output voltage waveform and magnetic field waveform. In addition, continuous operation will be performed at 25 Hz, and the heat of the switch and absorption circuits will be measured. For the module scheme, the effectiveness of the error detection system and maintenance scenario for easy and quick replacement will also be investigated.

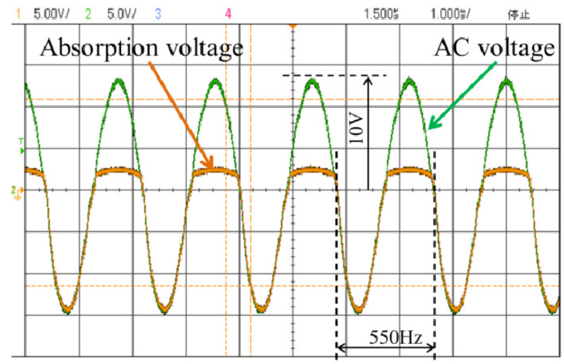

Figure 6: Measurement result of the terminal voltage when the absorption circuit SiC-MOSFET was turned off.

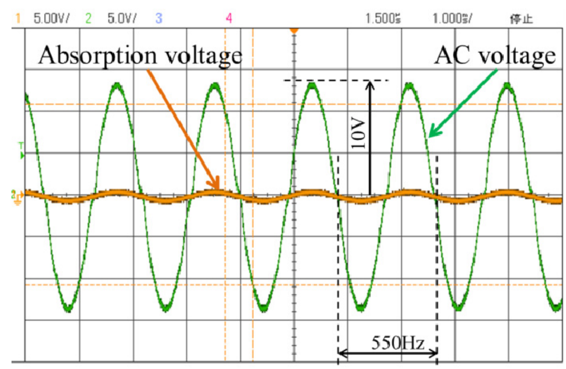

Figure 7: Measurement result of the terminal voltage when the absorption circuit SiC-MOSFET was turned on.

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