ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL082

DEVELOPMENT OF A NEW MODULAR SWITCH USING A NEXT-GENERATION SEMICONDUCTOR*

T. Takayanagi†, T. Ueno, K. Horino, J-PARC/JAEA, 319-1195, Tokai-mura, Japan

Abstract

An ultra-high-speed short pulse switch for high power devices has been developed by using SiC - MOSFET which is one of the next generation semiconductors. Semiconductor switches using SiC-MOSFETs are expected to substitute the thyratron, and they are designed by connecting many semiconductor switches in parallel-series for high power operation. In order to suppress the common-mode noise caused by switching, it is common to form a symmetrical circuit. However, as the number of parallel connections in the horizontal direction increases, the length of the parallel circuit becomes longer, and the output waveform is distorted due to time lag between the circuits. Therefore, we propose a radially-symmetrical type module switch which can equalize the circuit length regardless of the number of parallel circuit. The design and preliminary test results of two types of switch circuits, radially-symmetrical type and general line-symmetrical type are presented here.

INTRODUCTION

Transistors such as Si diodes, MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistor) and IGBTs (insulated gate bipolar transistors) are used as power elements [1]. The development of next generation semiconductors aimed at improving the performance of the power semiconductor is thriving. One of them is SiC (silicon carbide). SiC power semiconductors can realize "high withstand voltage", "low on resistance", "small switching loss". However, the current SiC device is in the process of development and has high withstand voltage but does not support high current. For this reason, in order to realize the semiconductor switch for high current power supply etc., it is absolutely necessary to construct a circuit by parallel multiplexing of elements [2-4]. Regarding multiplexing circuits of semiconductor switches, the usefulness of symmetric circuits has been confirmed as a method of reducing a common-mode noise caused by switching [5]. However, when the number of parallel connections is increased, since a large number of elements are arranged side by side, the length of the parallel circuit becomes longer and there is a difference in the distance between the elements. In the case of a switch circuit that turns on all the elements at the same time, a deviation occurs in the current propagation time between the parallel circuit. Since the output waveform from the switch is a superimposed waveform of the output waveform from each circuit, the superimposed waveform will be distorted if there is a deviation in the propagation time.

Therefore, we have conceived a radially-symmetrical type switch circuit in which parallel circuits are arranged on a circle so that the distances between elements are equal. With this circuit configuration, waveform distortion due to the propagation distance can be suppressed. We fabricated a modular switch assuming versatility combining SiC power semiconductor and radially-symmetrical circuit structure and evaluated its performance. In the evaluation, two types of circuits, radially-symmetrical type and line-symmetrical type, were fabricated and the waveform distortion of the output voltage was confirmed.

CIRCUIT DESIGN

Base circuits common to both circuits were designed. By changing the parallel connection structure of the base circuit, radially-symmetrical type and line-symmetrical type are constructed. Only for line-symmetrical type circuits, two kinds of distances between the parallel circuits of 50 mm and 300 mm were prepared so that the dependency of the difference in the distances between the circuits could be confirmed. The number of parallel circuits was set to 8 parallels in all circuits. Furthermore, the output voltage was doubled by stacking the boards in two stages, and the evaluation was carried out in the same way. For SiC semiconductor, SCT 3030 KL made by Rohm was used.

Base Circuit

The SiC semiconductor is operated as one element in a parallel circuit of one circuit with an output voltage of 800 V, an output peak current of 50 A. Figure 1 shows a block diagram of a base circuit which is made into a parallel circuit. In this circuits, in order to adjust the individual difference of the turn-on time, a gate waveform delay correction circuit is provided on the trigger line. Figure 2 shows the schematic diagram of the base circuit. This circuit was arranged in parallel, and a test circuit board of radially-symmetrical type and line-symmetrical type were fabricated.

Structure of Test Circuit for Measurement

The schematic diagrams of the radially-symmetrical type and the line-symmetrical type are shown in Figs. 3 and 4, respectively. Figure 5 shows the setup of output voltage measurement using the radially-symmetrical type.

In the case of the radially-symmetrical type, the output terminal on the P side is provided on the circumference of Φ 40 mm, and the eight terminals are connected on the back side of the circuit board and at the same potential. This point is the same as output P in Fig. 2. The distance between adjacent terminal is about 15.7 mm, which equally divides the circumference of diameter 40 mm. The N side is the reference potential of each base circuit and it is connected to the back side of the circuit board. The potential is grounded to the aluminum plate isolated by the insulator under the board. The central Φ20 mm aluminum rod is

† tomohiro.takayanagi@j-parc.jp

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL082

connected to the aluminum plate and it is at the same potential as the ground.

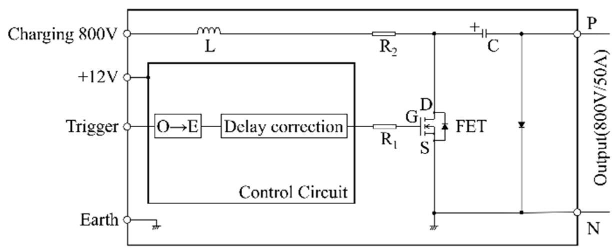

Figure 1: Block diagram of base circuit.

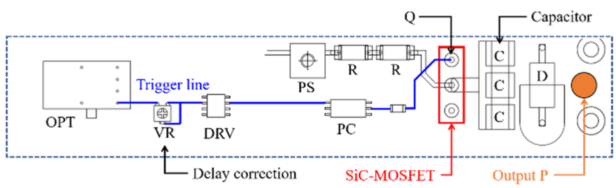

Figure 2: Schematic diagram of base circuit.

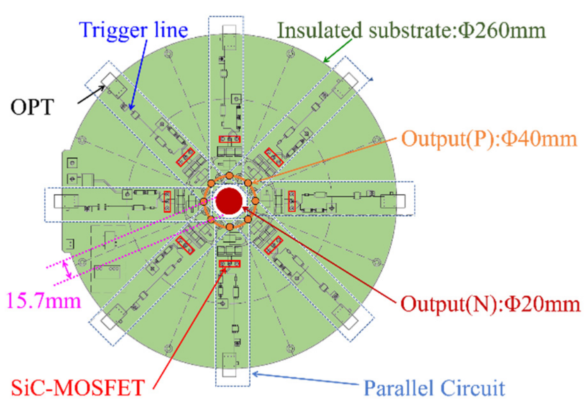

Figure 3: Schematic diagram of radially-symmetrical type base circuit.

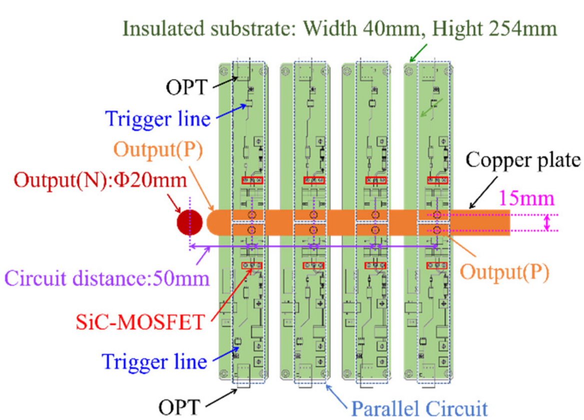

Figure 4: Schematic diagram of line-symmetrical type.

In the line-symmetrical type, the output terminal on the P side is connected to a copper plate with a width of 20 mm under the circuit board. The distance between the P terminals of the upper and lower opposed circuits is 15 mm. This distance is almost the same as radially-symmetrical type. N side is connected on the back side of the circuit board like the radially-symmetrical type and the potential is grounded to the isolated aluminum plate. The reference potential is obtained from an aluminum rod of Φ 20 mm and it is at the same potential as the ground. This point is the same as earth in Fig. 1. The line-symmetric type in Fig.4 shows a case where the distance between parallel circuits is 50 mm. Another symmetric type with a circuit distance of 300 mm is composed by changing only the distance using the same board for comparison in the test.

For all measurements, a combined resistive load of about 2 Ω (a 15 Ω resistor connected in parallel) was connected between the P terminal and the N terminal and the voltage across the resistor was evaluated.

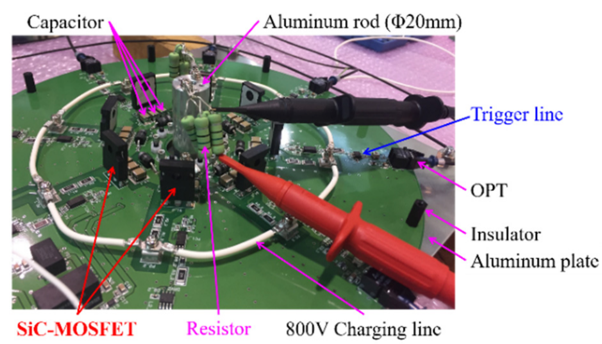

Figure 5: Situation of output voltage measurement using the radially-symmetrical type.

MEASUREMENT RESULT

Correction of Gate Timing

To prevent the time lag in gate timing, each gate waveform of all the symmetrical boards (using the same circuit boards for 50 mm and 300 mm) was measured at the Q position of the SiC-MOSFET in Fig.2, so that each gate timing was corrected by the delay circuit. Figure 6 shows all the adjusted gate waveforms of each type. This result shows that all parallel circuits operate without delay.

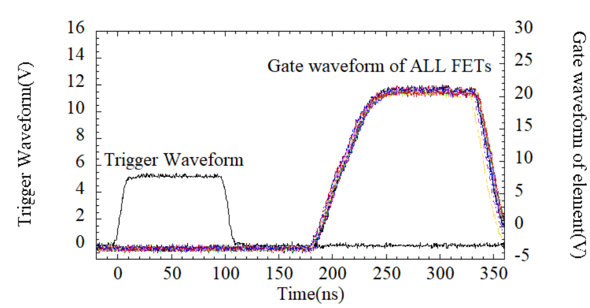

Figure 6: Measurements results of the gate waveform of all MOSFETS of each type.

Measurement Results of Output Waveform

The output voltage waveforms measured with three symmetrical circuits, these results are shown in Fig. 7. The time difference from the 10 % level to the 90 % level was defined as the rise time (Tr). The Tr of a radially-symmetrical

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL082

type was 48 ns and a line-symmetrical type was 54 ns for 50 mm and 74 ns for 300 mm. In the evaluation that the output voltage is doubled, each board is layered with an insulator in between. The P terminals are connected with a metal spacer, and the number of the optical gate signals is doubled. The measurement results are shown in Fig. 8 and the evaluation results of each Tr are shown in Table 1. The test setup with a parallel circuit distance of 300 mm and voltage doubled is shown in Fig. 9. The Tr became faster as the voltage increased, and the fastest Tr was the achieved for radially-symmetrical type. Furthermore, a sharp peak waveform and decay could be confirmed.

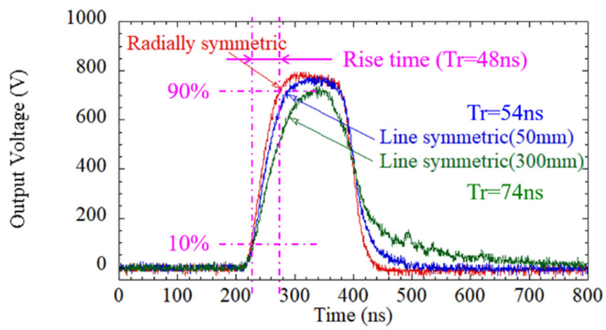

Figure 7: Measurement result of output waveforms by three symmetrical circuits.

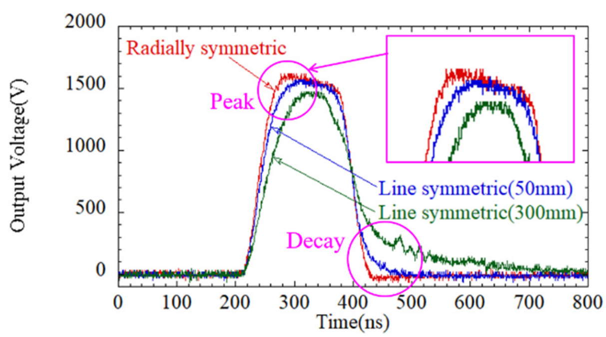

Figure 8: Measurement result of output waveforms when output voltage is doubled.

Table 1: Evaluation Results of each Tr

Type	One layer	Two layers
Radial	48ns	45ns
Line(50mm)	54ns	52ns
Line(300mm)	74ns	70ns

CONCLUSION

With the radially-symmetrical type, the Tr of the output voltage waveform became the fastest. Furthermore, since there is less distortion and the peak shape and decay are steep waveform shapes, it is ideal as an output waveform of high-speed short pulse. Using the delay correction circuit as shown in Fig. 6 makes it possible to correct the circuit length difference in principle even in the case of the line-symmetrical type. However, it is difficult to adjust if the number of circuits is large, and the waveform tends to be distorted due to inductance and stray capacitance. Even in circuit fabrication, it was easy for the radially-symmetrical type to make the distances of the parallel circuits equal, shorten the circuit length, and make the circuit impedance lower than the line-symmetrical type. It was confirmed that the radially-symmetrical type circuit is very useful for constructing multiple circuits was confirmed.

Based on the knowledge obtained in this study, we will develop a highly versatile modular switch, a semiconductor switch that substitute a thyratron using the LTD circuit [6, 7], and a power supply with an ultra-high-speed short pulse for accelerator.

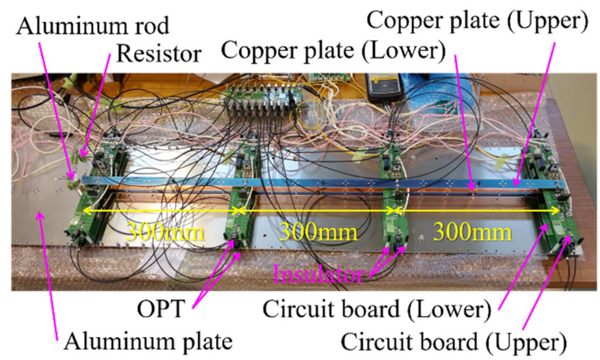

Figure 9: Test condition with a circuit distance of 300 mm and voltage doubled.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number JP17K06334. The authors would like to thank A. Tokuchi and Y. Mushibe (Pulse Power Japan) for their technical support, and thank M. Kinsho, K. Yamamoto and Y. Irie for their participation in fruitful discussions and continuous support.

REFERENCES

[1] T. Takayanagi et al., "Comparison of the Pulsed Power Supply Systems Using the PFN Switching Capacitor Method and the IGBT Chopping Method for the J-PARC 3-GeV", *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp.3800905, Jun. 2014

[2] C. Mitsuda et al., "Solid-State Compact Kicker Pulsar Using Strip-Line Type Blumlein with Sic-Mosfet In Spring-8", in *Proc. IPAC'16*, Busan, Korea, 2016, pp. 3585-3587.

[3] Yang Li et al., "Design and Development of Accelerator Magnet Power Supply Based on Sic-Mosfet", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3388-3390.

[4] K. Okamura and K. Takayama, "Development of an Induction Accelerator Cell Driver Utilizing 3.3 Kv Sic-Mosfets", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 567-569.

[5] K. Sato and H. Toki, "Synchrotron magnet power supply network with normal and common modes including noise filtering", *Nuclear Instruments and Methods in Physics Research* A 565 (2006) 351–357.

[6] W. Jiang, et al., "Pulsed Power Generation by Solid-State LTD", IEEE Transactions on Plasma Science, Vol.42, No.11, Nov. 2014m pp.3603-3608.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL082

[7] T. Takayanagi et al., “Development of a New Pulsed Power Supply with the Sic-Mosfet”, in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, pp. 3412-3414.