Introduction of Technologies for High-Voltage and Radio-Frequency Pulse Power Supply

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Abstract

Pulse power supply is equipment that generates a momentary large power output. In particular, this equipment is applied to plasma application fields such as film formation, environmental fields (exhaust gas treatment), etc.

We focused on high-speed switching characteristics and low-loss characteristics of the Silicon Carbide (SiC)-Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) developed in recent years, and established a series connection technology for semiconductor devices. In doing so, we realized variable pulse width (pulse width: 0.1 μs～), high-frequency operation (repetition frequency: 400 kHz～), high voltage (output voltage: ～−10 kV), high-speed operation (rise/fall time: 30 ns～), and developed a pulse power supply product and prototype not found in our product line. Application examples include a Pockels cell driver and a pulse power supply for film formation. We have confirmed high-voltage and high-frequency operation of −10 kV and 400 kHz.

1 Preface

Pulse power supply is equipment that generates a large power output in a pulse state for extremely short time of microseconds and nanoseconds. It is utilized in the technical field called Pulsed Power[(1)]. To cope with laser loads, the magnetic pulse compression system was adopted for the pulse power generated circuit[(2)]. In many cases, however, it was difficult to apply this system to plasma application fields (such as film formation and environmental fields “exhaust gas treatment or activated sludge treatment, etc.”).

To apply it to the plasma application field, we developed a product and prototype of a pulse power supply that can operate at high voltage and high frequency by controlling a high voltage switch. For the high-voltage switch, the Silicon Carbide (SiC)-Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) was applied to our developing product. The required high voltage and high-frequency were realized by making series connections. This paper introduces the operating principle of high-voltage and high-frequency pulse power supply, its circuit and some application examples.

2 Operation Principle of High-Voltage and High-Frequency Pulse Power Supply

Fig. 1 shows the main circuit configuration of a high-voltage and high-frequency pulse power supply developed as the product/prototype. The high-voltage and high-frequency pulse power supply equipped with the main switches (SW1 and SW2) is a device that applies a pulse-shaped voltage to a load by making ON/OFF control of each switch.

If power is supplied from an external DC power source and there is a voltage drop due to responsiveness, a capacitor (C) may be inserted. Resistors (R1 and R2) are inserted for the prevention of a ringing phenomenon possibly caused by a

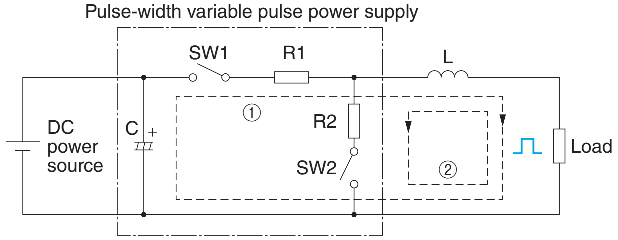

Fig. 1 Main Circuit Configuration of High-Voltage and High-Frequency Pulse Power Supply

A main circuit configuration of a high-voltage and high-frequency pulse power supply is shown.

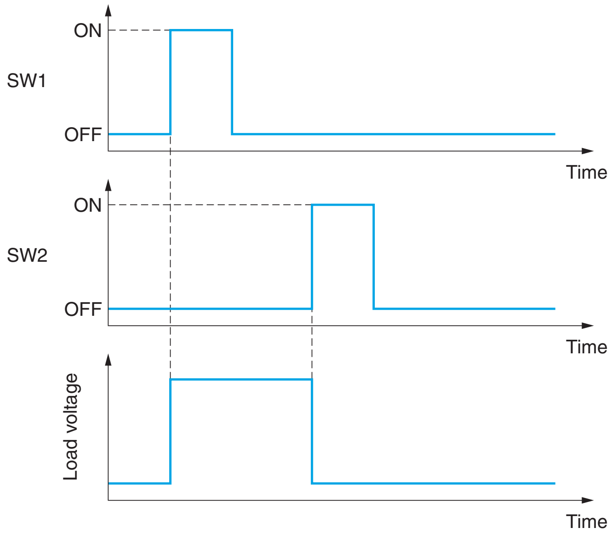

Fig. 2 Operation Timing Chart for High-Voltage and High-Frequency Pulse Power Supply

An operation timing chart for the high-voltage and high-frequency pulse power supply is shown.

floating inductance (L) and a load between the power source and the load. If the load is resistive, R2 and SW2 are not required. When the load is capacitive, on the other hand, R2 and SW2 are needed.

Next, Fig. 2 shows the operation timing chart assuming a capacitive load. To raise the load voltage, turn SW1 ON and SW2 OFF. At that time, the current flows from the DC power supply to the load along the route indicated by the dashed line ① in Fig. 1, raising the load voltage. To lower the load voltage, turn SW1 OFF and SW2 ON. At that time, a current flows through the route indicated by the dashed line ② in Fig. 1, causing the load voltage to drop.

3 Switching Circuit Configuration

Pulse power supplies for plasma applications require high-speed, high-voltage pulse output characteristics and high-frequency operation. High speed means a short rise/fall time (several tens of ns), and high voltage means a high peak voltage (several kV to several tens of kV). When a pulse is output using the circuit system shown in Fig. 1, the characteristics of the switching circuits (SW1 and SW2) themselves have a large effect on the pulse output characteristics. Below, we will introduce the configuration of the switching circuit for obtaining high-speed, high-voltage pulse output.

Table 1 Comparison of Power Device Characteristics

A comparison of power device characteristics applicable to high-voltage and high-frequency pulse power supplies is shown.

Device materials	Si-MOSFET	SiC-MOSFET			
No	1	2	3	4	5
Maker	Firm A	Firm B	Firm C	Firm D	
Released year	2012	2015	2016	2020	2021
Rated voltage (V)	1200			1700	
Shape	TO-247				TO-247-4L
Rated current (Peak current) (A)	12 (48)	14 (35)	12.5 (40)	48 (200)	
Rise time (ns)	11	19	11	10	7
Fall time (ns)	18.5	29	10	17	
ON resistance (mΩ)	620	280	160	35	

3.1 Selection of Power Device

Power devices for generating pulsed power include thyristors, Insulated Gate Bipolar Transistors (IGBTs), MOSFETs and others(3)-(5). There is no switch, however, that operates at several tens of nanoseconds and several tens of kV on SSa single device. To achieve high voltage by connecting devices in series, it is necessary to select a power device that operates in several tens of nanoseconds.

Table 1 shows a comparison of power device characteristics. Si (Silicon)-MOSFET can operate at high speed, but the ON resistance is large, and the loss is large. In recent years, technological innovation in SiC-MOSFETs has progressed. The devices were selected according to the timing of device release and the specifications of each device, and No.3 SiC-MOSFET was applied to the Pockels cell driver application and No.4 SiC-MOSFET to the pulse power supply for the plasma application field.

3.2 Configuration of Switching Circuit

Fig. 3 shows the configuration of the switching circuit. The switching circuit achieved high voltage by connecting elements in series. There are various device driving methods for achieving high voltage by connecting devices in series. If the elements are not switched at the same time, the voltage distribution will be disrupted and the elements may be damaged. In addition, considering the voltage sharing applied to each element during steady state and transient, a resistor and a capacitor were connected in parallel.

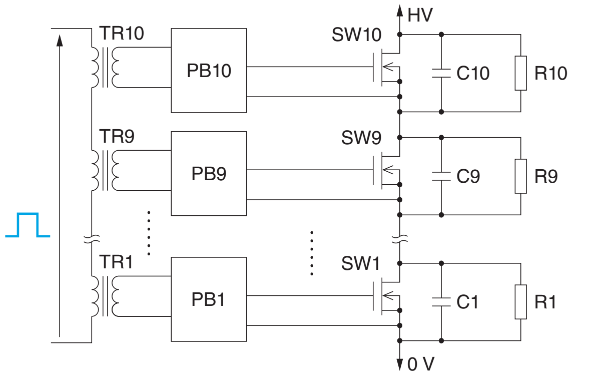

Fig. 3 Configuration of Switching Circuit

A switching circuit configuration is shown. Devices are connected in series and a pulse transformer system is adopted for the gate driving circuit. In consideration of voltage sharing, the respective devices are connected with resistors and capacitors.

Table 2 Main Specifications of EUV Pockels Cell Driver

Main specifications of the EUV Pockels cell driver are shown.

Item	Specifications
Output voltage	0~6 kV (Variable)
Repetitive frequency	0~120 kHz (Variable)
Load capacitance	10~40 pF
Output pulse width	0.1~2.0 μs (Variable)
Rise/fall time	30 ns or less
Jitter	4 ns or less
Cooling system	Water-cooled
Mass	16 kg or less
External dimensions	W270 × H290 × D210 mm or smaller

4 Pockels Cell Driver for Extreme Ultraviolet (EUV) Light Source Control

As a state-of-the-art photolithography light source, there is EUV with a wavelength of 13.5 nm. Our pulse power supply is used for the Pockels cell driver that controls the EUV light source. Table 2 shows the main specifications of the EUV Pockels cell driver. It is a positive polarity pulse power supply that can output high-speed, high-voltage pulses with variable output pulse width and high repetition rate, and jitter (variation width in the direction of the time axis) is extremely small. Furthermore, the power consumption of the Pockels cell driver itself has been reduced from 900 W to 600 W compared to other companies' conventional models.

Table 3 Main Specifications of Pulse Power Supply by Trial Production

Main specifications of the prototype of pulse power supply are shown.

Item	Specifications
Input voltage, Max. capacity	0~−10 kV (Variable), 70 kW
Output voltage	0~−10 kV (Variable)
Repetitive frequency	0~400 kHz (Variable)
Output pulse width	0.5 μs~∞ (Variable)
Rise/fall time	0.2・0.4 μs
Cooling system	Water-cooled

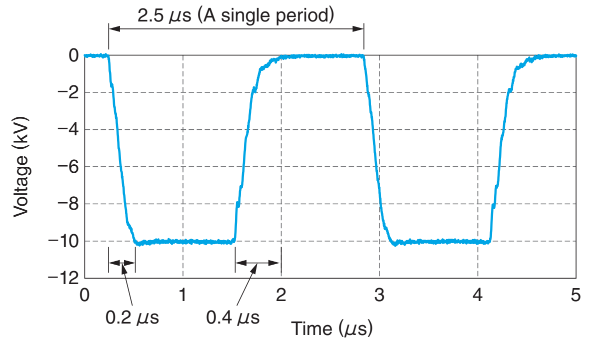

Fig. 4 Example of Output Voltage Waveform in 400 kW Operation

An example of an output voltage waveform is shown when a pulse power supply for plasma-applied fields is operated at 400 kHz. The output voltage is about −10 kV.

5 Pulse Power Supply for Plasma Application Field

The high-voltage and high-frequency pulse power supply is a device that outputs a pulse-shaped voltage through ON/OFF control of a main switch. If the high voltage/high frequency technology is established, we can adjust the polarity, frequency, output voltage, etc. according to the customer's request[6]. In recent years, there has been a demand for a high-voltage, high-frequency pulse power supply for plasma applications. We made a prototype power supply to meet that need. Table 3 shows the main specifications of the high-voltage and high-frequency pulse power supply. Fig. 4 shows an example of an actual output voltage waveform. We confirmed −10 kV high voltage output and 400 kHz high frequency operation.

6 Postscript

This paper introduced the operating principle and circuit of our high-voltage and high-frequency pulse power supply and its application examples.

In the future, we will work on higher voltages (up to 20 kV) and higher frequencies (up to 1 MHz) to meet customer needs. In addition to the application examples introduced in this article, pulse power supplies are used in various fields such as air cleaning, water treatment, etc. It is expected that their applications will continue to expand in the future. We will continue to strive to improve our technology and expand the application fields by increasing the variations of our products.

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