Product News

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Development of a high-output, highly stabilized power source using SiC power semiconductor technology

Potential for expanded use of X-ray free-electron lasers

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A joint development group comprising Hitoshi Tanaka, Division Director of the XFEL Research and Development Division at RIKEN's SPring-8 Center; Chikara Kondo, Chief Researcher of the Accelerator Machine Group at the Japan Synchrotron Radiation Research Institute's Light Source Division; and Takeo Mori, Business Group Leader at NICHICON CORPORATION's NECST Business Headquarters Business Group for Capacitor-Applied Systems & Equipment have developed a compact pulsed power supply using an SiC MOSFET[1] next-generation power semiconductor device that achieves both high output and high stability and allows the output current direction and size to be varied over a broad range.

These research results are expected to contribute substantially to the available time for experimental use and the efficiency of X-ray free-electron laser (XFEL)[2] facilities. Such facilities, which are being constructed around the world, use high-quality electron beams generated by linear accelerators.

To enclose in a compact cabinet a power supply that features both high output and high stability, the joint development group focused on an SiC MOSFET element that provided high withstand voltage and the ability to control large currents at fast switching speeds of more than 100 kHz. The main circuit was composed of chopper units, made up of SiC MOSFET elements and arranged in two series of five parallel units to achieve high output and high stability. In addition, the developed power supply employed a bypass current for routing surplus current to reduce the number of SiC MOSFET units in operation when the output current was small. This approach provided a sequence to ensure the control current was maintained at or above a certain level and achieve stability when output current was low.

This research will be published in the U.S. scientific journal *Review of Scientific Instruments* (June 18 edition), and posted prior to that date in the online edition (on June 15, or June 16 JST).

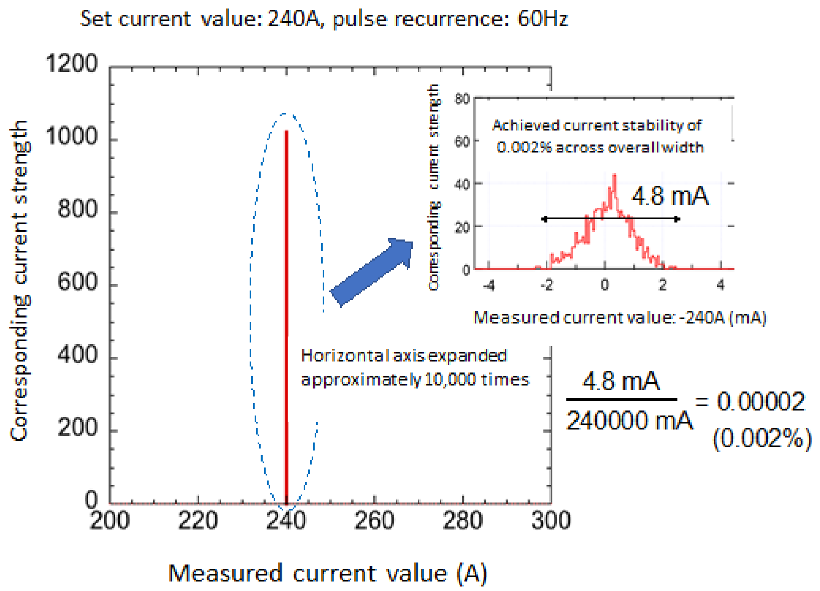

Figure. Current stability with achieved power operation

1. Background

Technological innovation in power semiconductors is proceeding at a remarkable speed. In a wide range of fields, expectations are mounting that incorporating power semiconductors will allow system performance to be improved substantially.

The RIKEN SPring-8 Center employs this state-of-the-art power semiconductor technology at its X-ray free-electron laser (XFEL) facility, SACLA[3]. The center uses the technology in its power supply for the magnet that apportions electron beams when switching between each of the pulses on its two XFEL beam lines. For soft X-rays and hard X-rays in the short-wavelength region, it is difficult to achieve laser amplification through population inversion of energy states (levels)[4] in typical gases and solids. For this reason, high-quality (high-luminance) electron beams at near the speed of light are routed to achieve interaction between the spontaneously radiated light and electron beams that are generated to form electron beams with a density modulation (contrasting density) corresponding to the laser wavelength, thereby amplifying the laser. Typically, this XFEL supplies lasers on only one beam line, located down-current from the linear accelerator that accelerates electron beams.

Given the rapid growth in research using X-ray lasers, increasing the number of beam lines and their usage time has been an urgent issue. For this reason, the joint development group aimed to construct a system that would provide multiple beam lines on the XFEL simultaneously, allocating them by using an electromagnet to rapidly change the magnetic field.

2. Development Method and Results

The main functions of the targeted pulse power supply were (1) the ability to operate at 60 Hz repetitions, (2) the ability to operate at any pattern for each of the 60 Hz repetitions, (3) rated output power: 0.24 MW (voltage: 1 kV, current: 240 A), (4) current stability with a variation of 0.002% or less at 240 A, and (5) a current setting range of -240 A to +240 A. This wide range of functions could not all be satisfied simultaneously with conventional resonant circuits[6] and pulsed power supplies using pulse forming networks (PFNs). In particular, these power supplies were unable to freely change current patterns for each pulse.

A four-quadrant power supply[8] was appropriate for controlling the current pattern at will, including the current size and direction. However, with conventional four-quadrant power supplies achieving current stability over a wide range—from large currents to ultrasmall currents—was problematic, and satisfying the other target functions at the same time was not possible.

With a four-quadrant power supply, it is possible to improve maximum output power and current stability by augmenting the functionality of the high-power elements used. Following consideration, the joint development group realized that it would be possible to simultaneously achieve main target functions (1) through (4) by connecting chopper units arranged in two series of five parallel units that comprised SiC MOSFET elements, which could maintain high withstand voltage characteristics of 1 kV or more and achieve high-speed switching in excess of 100 kHz at high currents of 100 A or more and controlling these with high-precision pulse width modulation (PWM)[9]. Based on this fundamental circuit, the group then conducted detailed designs of the actual power supply, optimized feedback control and assessed detailed circuit characteristics.

The final issue that remained was the instability of the power supply’s operation at near-zero currents. To address this problem, the group introduced a bypass circuit for pass on surplus current. Using a circuit to bypass current to the load (in this instance, an electromagnet) allows control current to be maintained at a certain level. Furthermore, by reducing the number of units in operation, the group employed a sequence that controlled the lower limit of the output current at one unit, achieving stable power supply operation at times of low output current. As a result, the group was able to achieve operations satisfying the target function of (5) for current ranges straddling zero.

Figure 1 shows a system diagram of the developed power supply, Figure 2 shows current stability for a 240 A output current, and Figure 3 shows photos indicating the exterior of the power supply unit and the chopper units. The power supply was produced by NICHICON CORPORATION.

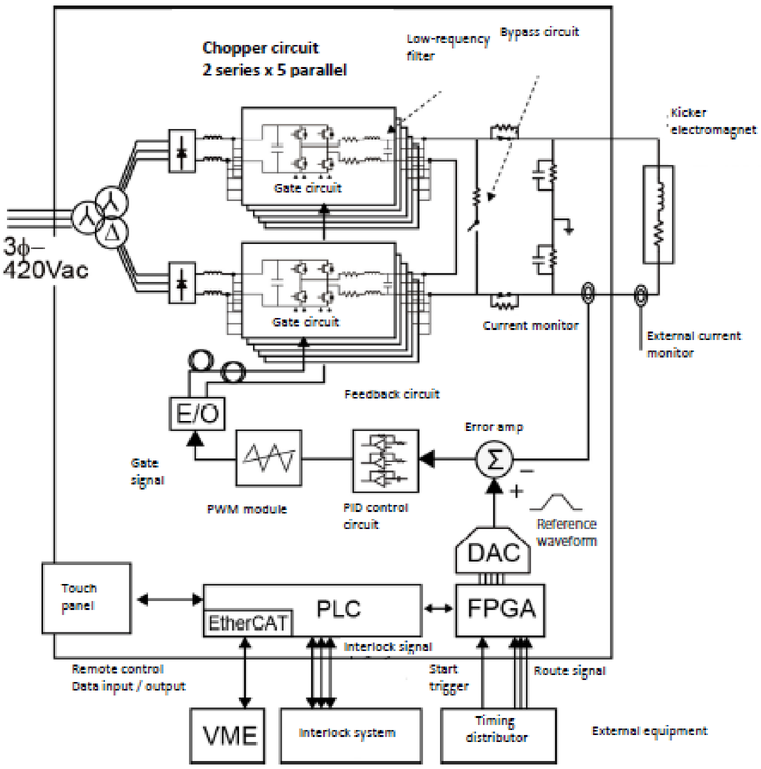

Figure 1. System diagram of the developed power supply

This power supply receives 420 V of three-phase electricity. Switching current is controlled by chopper units, connected two in series and five in parallel, generating a recurring 60 Hz with any pulsed current waveform. Output current is monitored, and feedback is controlled so that these values match the reference waveform.

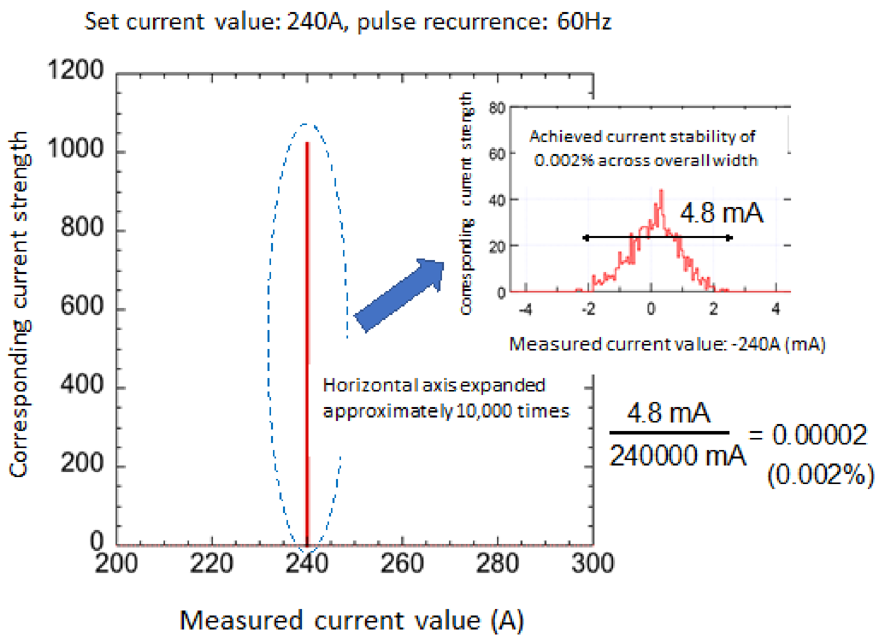

Figure 2. Current stability in the pattern operation

With a set current value of 240 A, the measured current value is divided when operating for a period of 17 seconds at a recurring 60 Hz. All data is held within the set value range of 240 A ±0.003 A, obtaining stability of 0.002% over the entire width.

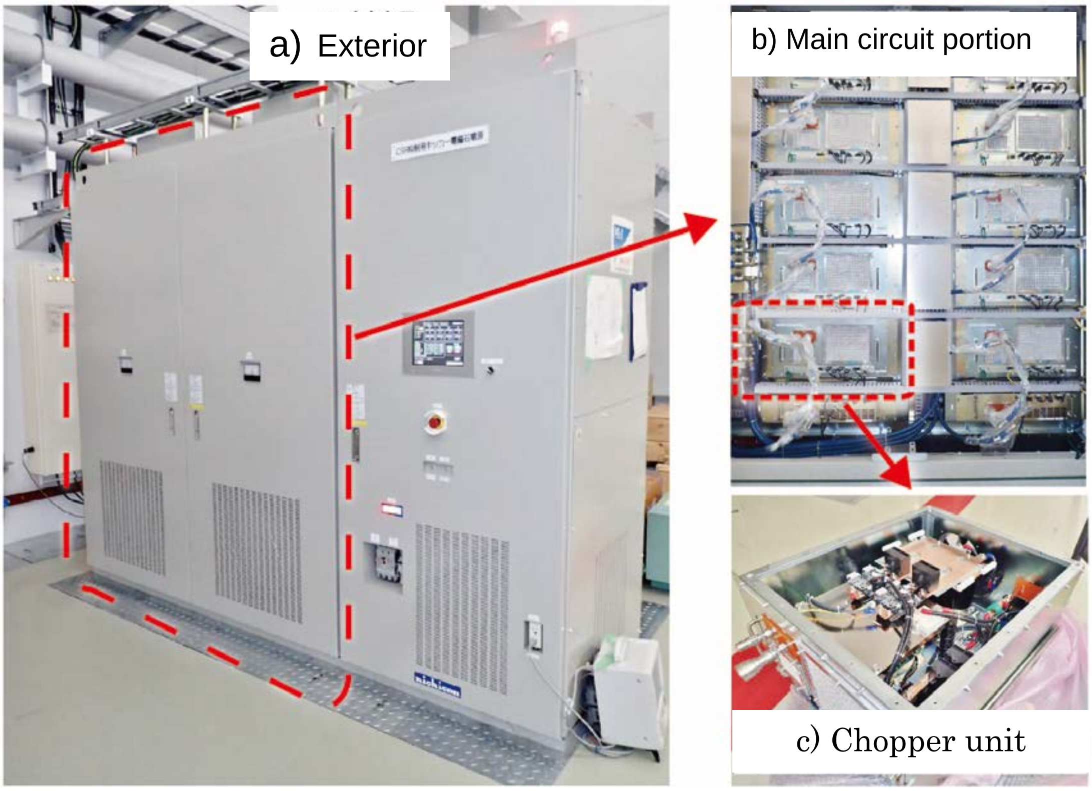

Figure 3. Exterior of the developed pulsed power supply unit and the chopper unit, which is the central part of the circuit

a) shows the exterior of the pulsed power supply, which measures 2.7 m high by 3 m wide by 1 m deep. b) shows the content of the left side of the cabinet, which houses the main circuit, made up of two chopper units in series and five in parallel. c) shows the inside of a chopper unit.

3. Future Expectations

Applying four-quadrant power supplies to the area of power semiconductor devices, which are progressing at a remarkable pace, led to success in the development of a power supply capable of achieving functions that had not been possible in the past: superior current stability at high power and the ability to change current patterns for each pulse of output. Based on these research results, in February 2016 SACLA succeeded for the first time in substantially enhancing laser quality in XFEL pulse distribution operations. These distribution operations went into service operation as standard operating mode in September 2017, achieving an increase in experimental time available for use.

It is anticipated that other XFEL facilities facing the need for expanded usage going forward will introduce the same type of distribution system and power supply to enhance operating efficiency. Furthermore, the developed power supply can be applied to the variety of instruments driven by the output. It is expected that applying these results to the operation of instruments using any current and voltage pattern can contribute to advances in a variety of production systems.

4. Information on the Research Paper

<Title>
A stable pulsed power supply for multi-beamline XFEL operations
<Authors>
Chikara Kondo, Toru Hara, Toru Fukui, Takahiro Inagaki, Hideki Takebe, Shingo Nakazawa, Kenji Fukami, Yusuke Kawaguchi, Hideaki Kawaguchi, Yuji Otake, and Hitoshi Tanaka
<Journal>
Review of Science Instruments

5. Supplementary Explanations

[1] SiC MOSFET

A silicon carbide (SiC) transistor power semiconductor element. Compared with silicon (Si) power conductor elements, which are currently mainstream, these elements permit switching at higher speeds and with lower power loss. At higher frequencies, inductors and other structural components can be made smaller, permitting the miniaturization of power supply products, reducing the amount of material used, and decreasing the amount of energy required for product transport, thereby creating expectations of a variety of energy-conserving effects rippling outward.

[2] X-ray free-electron laser (XFEL)

A pulsed laser in the X-ray domain realized through the development of accelerator technologies in recent years. Different from conventional lasers that used semiconductors and gases as oscillation media, this laser uses as a medium electron beams, which move at essentially the speed of light in a vacuum. As a result, there are theoretically no limits to wavelength, making this the only laser that can be used in the X-ray domain. XFEL is an acronym for X-ray free-electron laser.

[3] SACLA

This is an XFEL facility, the first in Japan, which was jointly constructed by RIKEN and the Japan Synchrotron Radiation Research Institute. One of five national key technologies under the Science and Technology Basic Plan, this facility was constructed and kitted over the period of a five-year plan beginning in fiscal 2006. Completed in March 2011, the facility was named SACLA, an acronym for SPring-8 Angstrom Compact free-electron Laser. The first X-ray oscillations began in June 2011, and the facility went into service in March 2012. The facility is capable of X-ray laser oscillations of less than 0.1 nanometer (10 billionth of a meter), the shortest wavelengths in the world.
For details, see http://xfel.riken.jp/

[4] Energy state (level)

The electrons contained in atoms and molecules have discretized energy states (levels) characteristic of these systems and do not exist at a given energy stage. Energy states, in order from low energy levels are called ground state, first excited state, and second excited state.

[5] Population inversion

Within a system, normally more atoms exist in low energy states than in higher ones. Taking the ground state and first excited state as an example, more electrons exist in the ground state. If light is impinged from an outside source, exciting the ground-state electrons, they can be elevated to the first excited state, making likelihood of electrons existing at the first excited state higher than that for the ground state. This reversal of the occupancy ratios between energy states is called population inversion. This state is necessary for stimulated emission, needed for laser amplification.

[6] Resonant circuit

The circuit used to move electrical energy between the coil and capacitor. Current oscillations are generated at the specific resonant frequency determined by the characteristics of the coil and capacitor.

[7] Pulse forming network (PFN)

An electric circuit that contains numerous capacitors and coils connected in a ladder shape. Conduction via a high-speed, high-current switch connected at the end of the circuit causes electrical energy stored in the capacitors to be discharged in order through the coil, with current output in rectangles and other predetermined patterns.

[8] Four-quadrant power supply

With this type of power supply, voltage and current can be output in both the plus and minus polarity directions according to magnetic and other loads. In addition, when electricity is supplied to the load, the electric power stored in the load can be absorbed (recovered).

[9] Pulse width modulation (PWM)

A chopper circuit controls current as the switch is repeatedly turned on and off. With this control method, varying the width when the switch is on allows the size of the average passing current to be adjusted.