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HIGH PRECISION DIGITAL CONTROL MAGNET POWER SUPPLIES

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Abstract

We developed high-precision digital control magnet power supplies aiming at next-generation light sources such as SPring-8-II. The control system consists of a high-precision ADC circuit and an FPGA that processes proportional-integral control and pulse-width modulation. Using the system, the current ripple and long-term stability (8 hours) of the power supply are controlled within 20 ppm. The power supply can be made to fit various magnets by readily adjusting feedback parameters. We also developed a function to synchronize the timing of multi-channel outputs such as three outputs for sextupole steering magnets. The newly developed power supplies have been introduced to the next-generation 3 GeV light source, NanoTerasu, in Japan.

INTRODUCTION

In the past few decades, many laboratories have developed magnet power supplies (PS) using digital feedback control [1]. Compared with conventional analog feedback control, digital feedback control offers greater flexibility in the control system design and makes relatively easy to achieve complex operations such as cooperative operation of multiple switching devices. In addition, because the feedback control parameters in a digital control system can be easily adjusted, the control parameters can be optimized on site. This characteristic allows one type of PS to be commonly used in multiple types of magnets.

We have developed high-precision DC power supplies for magnets using digital control technology for next-generation synchrotron radiation facilities such as SPring-8-II [2]. In this study, we developed more practical functions for actual operation, such as multi-channel synchronization. Using this technology, we designed and mass-produced magnet PSs for NanoTerasu, which is currently constructed in Sendai, Japan [3]. We also introduced a PS switcher that can quickly switch a power line connection from a troubled PS to a backup PS in a failure event.

DETAIL OF MAGNET PS

Concepts

The digital-controlled magnet PS was designed as a switching PS, which can achieve high precision and efficiency. The output current was measured by a DCCT and converted to a digital value using a 24-bit ADC circuit. It is feedback controlled by using proportional-integrated (PI) compensation and pulse width modulation (PWM) in an FPGA.

In order to reduce production costs, small-current PSs were designed as DC-link type sharing an AC-DC rectifier, a remote communication module, and a local operation device. The details of the PS are explained in Ref. [4]

A steering magnetic field is formed by winding three pairs of auxiliary coils around a sextupole magnet (SxM) and passing a balanced current through them at a constant ratio. When adjusting the magnetic field, it is necessary to change the current while maintaining current balance. The PSs are required a current deviation within 50 ppm over the entire current range.

In the event of a PS failure, we devised a method to restore the operation as soon as possible. For high power PSs, an output line switcher was developed so that the failure PS could be switched to a backup PS.

High Power PS for Family Magnets

A high-power PS was used to excite multiple magnets connected in series and required a high-current, high-precision. We designed a high-power PS in which multiple switching units are connected in parallel.

The switching timings of the units are phase-shifted from unit to unit to increase the effective switching frequency and suppress current ripple. The current balance between the switching units is controlled by the FPGA.

The control unit digitizes the measured current signal using an ADC circuit, processes the feedback control, and generates PWM signals in the FPGA. Programmable Logic Controller (PLC) modules process operational control, remote communication via EtherCAT, and interlock.

DC-link PS for Steering Magnets

The PS that excites the steering magnet (STM) outputs a small current of 5–16 A, and a large number of quantities with several hundred units are required. We designed it as follows: One control unit can be connected to up to eight output units. The control unit is equipped with an AC-DC conversion circuit, a PLC-CPU module, a remote communication device, and a local control panel. AC 200 V is converted to DC 280 V by the rectifier circuit, and the DC power is supplied to multiple output units. The control unit communicates with the output units via CAN to control the output operation, set the current and feedback parameters, and check the status.

One output unit has two or three power circuits and one control board with an FPGA. Each power circuit converts 280 VDC to an appropriate voltage using a DC-DC converter. It is then switched using a full-bridge circuit to

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enable a bipolar output. The output currents are measured by DCCTs and high-precision ADC circuits and are controlled by the FPGA with PI and PWM control.

For the STM PS, the precise current stability with 50 ppm is required in all current regions including 0 A region. In PWM control using unipolar switching, the average value of output current $\overline{I_{out}}$ is estimated by

$$\overline{I_{out}} = \frac{V_{DC}}{R_{mag}} \frac{t_g}{T_{SW}},$$

where t_g is gate pulse width of a switching device, V_{DC} is DC-link voltage, R_{mag} is a load resistance, and T_{SW} is a switching cycle, respectively. When the output current is small around 0 A, the gate pulse width decreases to very short time. For example, if the switching cycle is 50 kHz, the DC-link voltage is 10 V, and the load resistance is 0.1 Ω, the gate pulse width becomes about 2 ns for 0.01 A output current. For such a very short gate width, general switching devices cannot respond and the current stability deteriorates.

To avoid this instability in the small current region, we developed an alternative bipolar switching method in that switching is performed alternately at positive and negative outputs. As shown in the middle right of Fig. 1, the positive and negative outputs alternate every half cycle, and the current is adjusted by balancing the gate pulse widths $(t_{g+}, t_{g-})$of the positive and negative outputs. The sum of the pules widths, $t_{sum} = t_{g+} + t_{g-}$, is about 1 µs. The averaged current is represented as,

$$\overline{I_{out}} = \frac{V_{DC}}{R_{mag}} \frac{(t_{g+} - t_{g-})}{T_{SW}}.$$

In the lower part of Fig. 1, we compared the current ripples obtained using the unipolar switching and the alternative bipolar switching method. Using the unipolar switching method, the current ripple increased up to 500 ppm in the small current range, whereas using the alternative bipolar switching method, the ripple was reduced to 20 ppm.

When adjusting the steering magnetic field of the SxM, the current balance of the three pairs of auxiliary coils should be kept constant while the current is changed, to suppress higher-order magnetic fields. Therefore, three pairs of auxiliary coils are excited by a single output unit with three outputs. The three outputs were controlled by a single FPGA, and the timings of the current change are synchronized. The steps of the current change are calculated by PLC-CPU of the control unit to keep the current balance of the three outputs. Then the control unit sends a set value of the current every 20 ms. Figure 2 shows the current waveforms when the current set of the three outputs is changed from (1A, 2A, 1A) to (0.7A, 1.4A, 0.7A). It indicates that the change timings of the three outputs are synchronized and that the change of output #2 is double that of the other outputs.

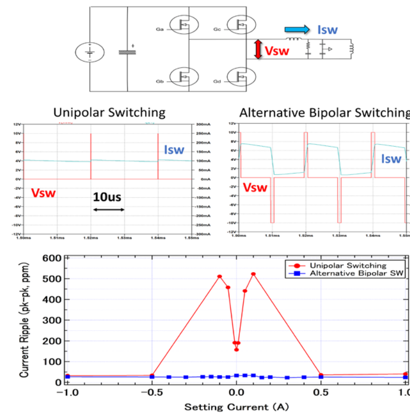

Figure 1: (Upper) Schematic layout of switching circuit. (Middle) Simulated waveforms of current and voltage in unipolar switching(left) and alternative bipolar switching (right). (Lower) Measured current ripple dependence on setting current for two switching methods

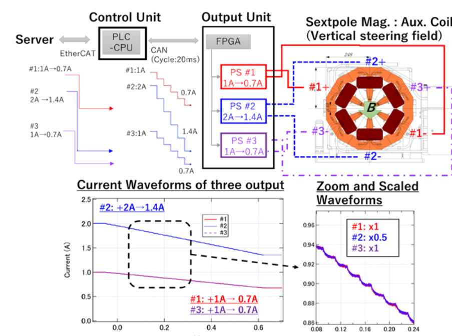

Figure 2: (Upper) Block diagram of steering PS and auxiliary coils of sextupole magnet. (Lower left) Current waveforms of three outputs when the currents are changed from (1A, 2A, 1A) to (0.7A, 1.4A, 0.7A). (Lower right) Zoomed and scaled waveform.

PS Switcher

If a family PS fails, we should switch the power line of the family magnet from the failed PS to a backup PS, to resume the beam operation. We introduced a switcher system to reduce the restart time. The switcher is equipped with power lines of multiple normal PSs and the backup PS, and it is possible to switch the power lines with bus bars. The switcher is also equipped with DCCTs for external monitoring, so that the output current can be continuingly monitored. Figure 3 shows the full view of the switcher and busbars installed to switch the backup power line.

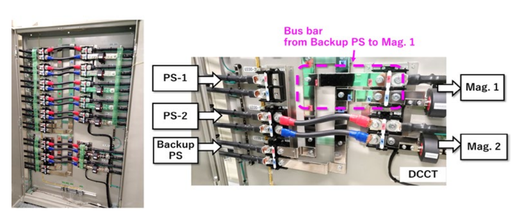

Figure 3: (Left) Full view of PS switcher. (Right) Photograph of power line connection switched from PS 1 to backup PS.

MAGNET PS IN NANOTERASU

NanoTerasu consists of a 3-GeV linac (Li), beam transport (BT), and a storage ring (SR) with 16 cells. In the Li and BT, some bending magnets (BMs), quadrupole magnets (QMs), STMs, and magnetic lenses were installed and excited using relatively small current PSs of 5–20, and some BMs, QMs, and DC septum magnets require large current PSs of 100–300 A. In the SR, BMs, QMs, and SxMs are connected in series to form a family, and each family is excited by one main PS at 50–650 A. The SxMs are equipped with auxiliary coils that behave as steering magnets with balanced currents. Q-auxiliary PSs are connected to some QMs, which allows the current to be adjusted individually. The family PSs were installed in a PS room, and DC-link PSs were installed in 19-inch racks located at the tunnel-side passage.

The magnet configuration for one cell in the SR is shown in Fig. 4. The specifications of the PSs are listed in Table 1. We adjusted the control parameters of these power supplies to be suitable for each magnet after installation by utilizing the characteristics of the digital control.

Table 1: Specifications of Magnet PSs in NanoTerasu

PS Name	Polarity	Out -put	Current/ Voltage	Quantity (Backup)
U650	Unipolar	1	650A/400V	2 (1)
U350	Unipolar	1	350A/200V	4 (1)
U50	Unipolar	1	50A/50V	3 (1)
U250	Unipolar	1	250A/110V	6 (1)
U330	Unipolar	1	330A/60V	3 (0)
U170	Unipolar	1	170A/30V	5 (1)
U300	Unipolar	1	300A/20V	1 (0)
B5a	Bipolar	3	+/- 5A/4V	46 (3)
B5b	Bipolar	3	+/- 5A/10V	19 (1)
B12	Bipolar	2	+/- 12A/20V	17 (1)
B16	Bipolar	3	+/- 16A/8V	133 (4)
U20	Unipolar	2	20A/10V	6 (1)
AUX9	4-Quad.	2	+/- 9A/20V	5 (1)
AUX20	4-Quad.	2	+/- 20A/9V	50 (2)

SUMMARY

We designed a magnet PS using digital control technology for the next-generation synchrotron radiation facilities. High-power PSs for family magnets consisted of multiple switching units. DC-link PS for the steering magnets consisted of one control unit and up to eight output units. The DC-link PS is able to control the current stably even in a small current region by the alternative bipolar switching method. In addition, by controlling the current of the three outputs with one FPGA, it is possible to change the steering current of the SxM while maintaining the balance. The developed PSs were introduced into the next-generation 3 GeV light source, NanoTerasu.

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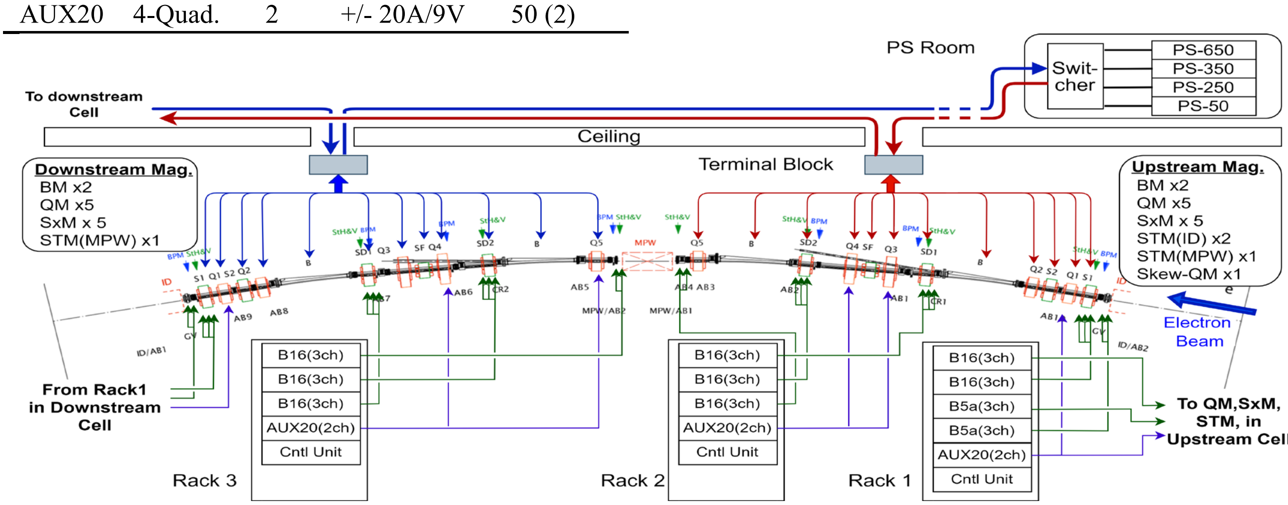

Figure 4: Schematic layout of magnets and power supplies for one cell in storage ring in NanoTerasu.