HIGH-STABILITY MAGNET POWER SUPPLIES FOR SUPERKEKB

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Abstract

For the SuperKEKB, over 2,000 of magnet power supplies were recycled and around 300 of power supplies were newly fabricated. The newly fabricated power supplies include high performance power supplies: the main bending/wiggler magnet power supplies and the power supplies for final-focus superconducting magnets installed around an interaction point. High power tests were performed and the results are reported.

INTRODUCTION

KEKB [1, 2] was the leading electron-positron collider in the world. Its recorded peak luminosity is 21.083×10^{33} cm^{-2} s^{-1}. KEKB concluded its operation in June 2010 to start the upgrade for SuperKEKB [3] aiming 40 times higher luminosity. SuperKEKB has been operated in a phased manner. On February 2016, a test operation was started and successfully finished on June, where a basic machine tuning, a low emittance beam tuning and a vacuum scrubbing were carried out (Phase 1). After the phase 1, the SuperKEKB final-focus superconducting magnets system (QCS) was installed around the interaction region, and Belle II detector [4] was also rolled into the interaction point. At the phase 2, squeezing beta at the interaction point and beam collision tuning are planned. Physics data taking will also start. At the phase 3, physics run with the full Belle II is planned.

The SuperKEKB Main Ring (MR) system [5] is consisting of more than 1700 water-cooled normal-conducting magnets and about 900 air-cooled normal-conducting magnets. The QCS is one of the most important component for a challenging luminosity. The system consists of 8 superconducting main magnets, 4 superconducting compensation solenoids and 43 superconducting corrector coils [6, 7, 8].

During Phase 1, the MR magnet system worked well, which contributed greatly to the smooth start-up of the MR. Over 2,000 of magnet power supplies used in KEKB are recycled, where they were overhauled except for the small-class power supplies such as for steering or corrector magnets. More than 300 of magnet power supplies were newly fabricated, tested and installed.

The magnet power supplies for the SuperKEKB MR and QCS are listed in Table 1, where the power supplies are classified by their rated output power.

The newly fabricated power supplies include high performance power supplies for the main bending magnets, the wiggler magnets and the QCS main magnets. These power supplies were designed aiming high performances for its output DC current: current setting resolution < 0.1 ppm, current stability < 2 ppm/24 hrs., temperature coefficient < 0.1 ppm/K, and current ripple < 1 ppm. In this report, the developments for such a high-stability power supply are reviewed.

Table 1: SuperKEKB Magnet Power Supplies.

MR magnet power supplies

Rated output power (Typ. current)	Number of Power supplies (A)	Number of Power supplies (B)	Loads
0.95 MW (860 A)	2	0	Main bends.
0.4 – 1 MW (1.4 kA)	9	0	Wigglers
0.1 – 0.5 MW (500 A)	0	18#	Main quads.
2 – 105 kW (500 A)	92	335#	Local-bend. /quad. /sext.
0.3 – 2.4 kW (±10 A)	138	1681	Steering/ correctors

QCS magnet power supplies

Rated output power (Typ. current)	Number of Power supplies (A)	Number of Power supplies (B)	Loads
30 kW (2 kA)	8	0	Main quads.
10 kW (500 A)	3	0	Anti-solenoid.
0.7 kW (±70 A)	43	0	Correctors

(A): Newly fabricated
(B): Recycled (# overhauled)

ACHIEVED CURRENT STABILITY OBTAINED IN PHASE 1 OPERATION

Fast of all, the achieved test result for an output current stability of a SuperKEKB main bending magnet power supply, which is obtained in Phase 1 operation, is shown in Fig. 1, comparing with one of main bending magnet power supply of KEKB.

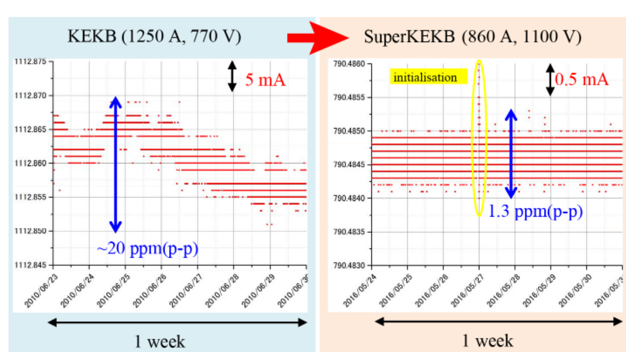

Figure 1: Achieved current stability.

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The output current stability of the new power supply has improved by the order of magnitude higher stable compared with the past KEKB power supply. The sufficiently high reproducible current value is also can be seen before and after the initialization operation done on the maintenance day.

DEVELOPMENT OF HIGH-STABILITY POWER SUPPLIES

Figure 2 shows a schematic of a current control loop of the QCS prototype power supply, whose rated output is DC 2 kA – 10 V. In order to measure a normal-mode current, two DC current transducers (DCCTs) are positioned on the positive and the negative sides of the output terminal of the power supply, respectively. The average value of these output signals is used as the normal-mode output current value of the power supply. The measured output current is used as the input for the analog current control loop, which keeps the output current constant and reduces the normal-mode current ripple.

A digital feedback loop is also prepared for higher-precision current control. The output signal of the DCCT on the negative side of the output terminal is preciously measured using a Keithley model 2002 digital multimeter. The output signal of the DCCT on the positive side is not used in the digital feedback loop, because there is no contribution of the common-mode component in a relatively slow control loop as follows. After every few tens of a second, the measured digital value is compared with the current setting value, and the error is fed into a 24-bit control board.

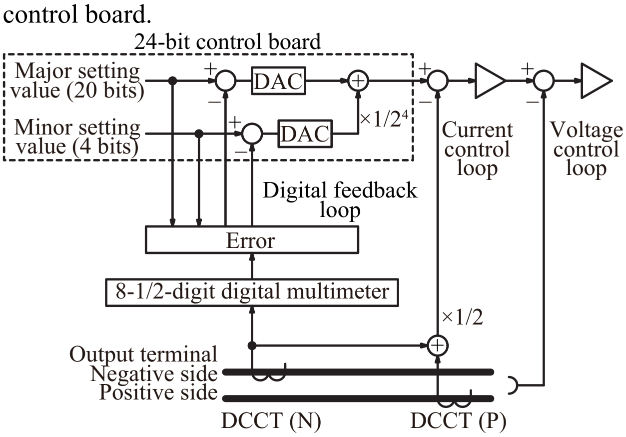

Figure 2: Schematic of a current control loop with digital feedback loop.

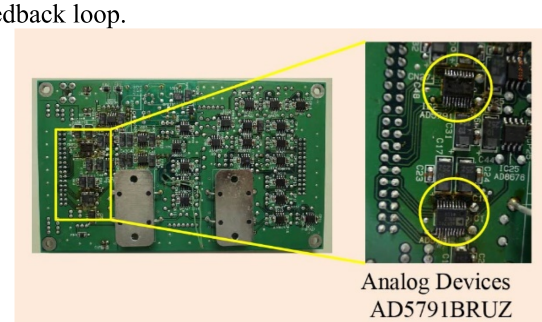

Figure 3: Two 20-bit DAC's 24-bit control board.

The 24-bit control board is developed using two 20-bit digital-to-analog convertors (DACs) (Analog Devices, AD5791). The 24-bit digital value for the current setting is divided into 20 major bits and 4 minor bits values. The former is an input for the DAC for coarse tuning, and the latter is an input for another DAC for fine tuning. After dividing the output of the fine DAC by 2^4, it is added to the output of the coarse DAC. Figure 3 shows the photograph of the developed 24-bit control board, where two DACs can be seen. A test results of the board is shown in Fig. 4, where 1 least significant bit (LSB) (= 0.6 µV) response can be seen.

The developed 24-bit control board has been applied to the QCS main quadrupole magnet power supplies. It was feared, however, that the monotonicity might be lost when the major DAC is changed by 1 LSB as explained by Fig. 5. In order to avoid such a failure in monotonicity, we choose AD5791B, whose integral non linearity (INL) is enough small: ±0.5 LSB typ. and −0.2 to +0.6 LSB as a test result. Just to be on the safe side, another type of a 24-bit control board is also developed and applied to the MR main bending/wiggler magnet power supplies. The 24-bit control board uses sixteen (= 2^4) 20-bit DACs, so that these sixteen outputs are simply summed up.

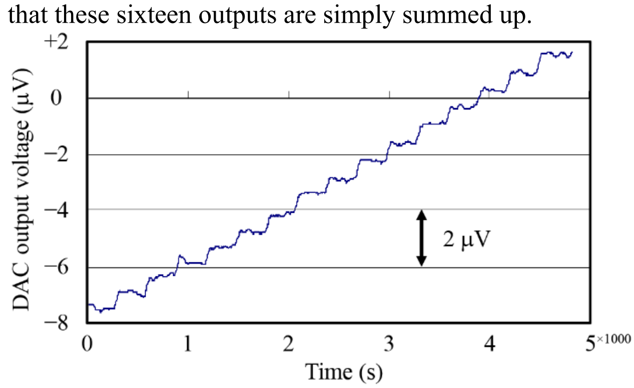

Figure 4: Test result of 24-bit board. Increasing DAC input digital value by 1 LSB, that is corresponds to 0.6 µV = 10 V full scale/ 2^{24}, DAC output voltage is measured by Keithley model 2002 digital multimeter.

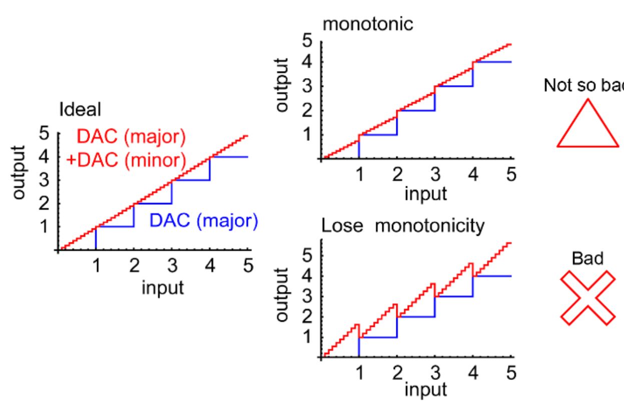

Figure 5: Care must be taken to the monotonicity of two DAC's 24-bit system. It is required for monotonic control, that INL should be smaller than ±0.5 LSB at least.

As mentioned above, the digital current loop is added to the analog current loop. Sometimes, such an additional loop disturbs the control system. However, the system stability is not affected because the target frequency range between the analog and digital current loop is different. While the analog current control loop works continuously, the digital current control loop periodically (typically every 60 s) modifies the current setting value with reference to the preciously measured output current, so that the error caused by the analog circuit can be compensated.

For the digital feedback loop, DCCT is one of the key components. For this purpose, a Hitec TOPACC DCCT is adopted. The main specifications are shown in Table 2. In order to suppress the influence of temperature, electronics modules of the DCCTs and the digital multimeters are placed inside a constant climate cabinet.

Table 2: Specifications of TOPACC DCCT

Rated output	10 V full scale
Bandwidth	DC – 500 kHz
Temperature coefficient	< 1.5 ppm/K
Linearity error	< 2.5 ppm

The test result of the current control loop with digital feedback loop is shown in Fig. 6. The current setting value and the output current of the model power supply (500 A, 15 V) are measured in the enabled and disabled digital feedback loops. When the digital feedback loop is disabled, the current setting value is constant; the output current is controlled by only the analog current control loop and is fluctuated due to such as the temperature dependence of the analog circuit. Once the digital feedback loop is enabled, it is clearly observed that the current setting value is corrected every 60 s by the digital feedback loop. The current stability obtained was within 1 ppm/h ($\sigma = 0.16$ ppm).

CONCLUSION

Developments of the high-stability power supplies for SuperKEKB are reviewed. The current control loop with digital feedback loop and the 24-bit control board lead to 1.3 ppm /week of high current stability, as the result.

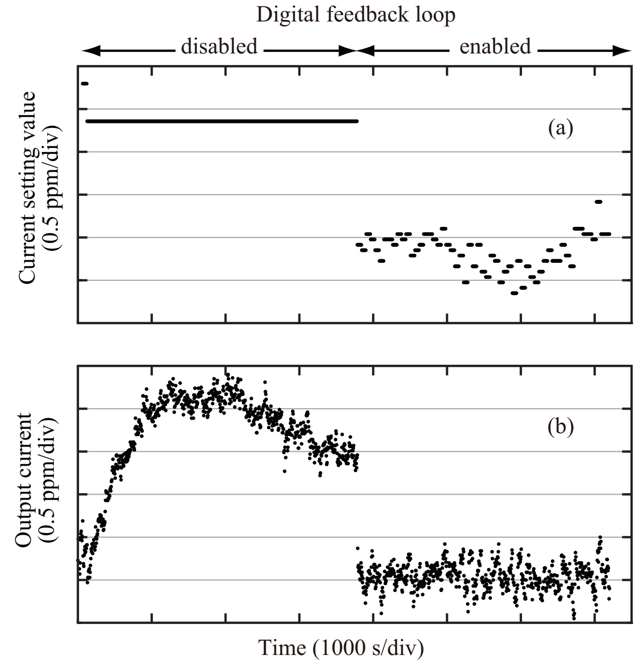

Figure 6: Control test result. (a) The current setting values. Although originally a digital value, it was converted to analog here. In both the cases of the digital feedback loop: disabled and enabled, (b) an output current of the model power supply (500 A, 15 V) is measured.

REFERENCES

[1] T. Abe *et al.*, "Achievements of KEKB", *Prog. Theor. Exp. Phys.*, vol. 03A001, 2013.

[2] T. Abe *et al.*, "Commissioning of KEKB", *Prog. Theor. Exp. Phys.*, vol. 03A010, 2013.

[3] Y. Ohnishi *et al.*, "Accelerator design at SuperKEKB", *Prog. Theor. Exp. Phys.*, vol. 03A011, 2013.

[4] Belle II Technical Design Report, KEK Report 2010-1, (2010). [Online]. Available: `http://www-superkekb.kek.jp/documents/B2TDR.pdf`

[5] M. Masuzawa *et al.*, "Commissioning Status of SuperKEKB Main Ring Magnet System", presented at IPAC"17, Copenhagen, Denmark, May 2017, paper WEPIK010, this conference.

[6] N. Ohuchi *et al.*, "Design of the superconducting magnet system for the SuperKEKB interaction region", in *Proc., NA-PAC'13*, Pasadena, California, USA, 2013, p. 759.

[7] B. Parker *et al.*, "Superconducting corrector IR magnet production for SuperKEKB", in: *Proc. NA-PAC'13*, Pasadena, California, USA, 2013, p. 1241.

[8] H. Yamaoka *et al.*, "Solenoid field calculation of the SuperKEKB interaction region", in: *Proc. IPAC'12*, New Orleans, USA, 2012, p. 3548.

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