Power Supplies for Superconducting Magnets at KEKB-IR

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Introduction

The B-factory (KEKB) is under construction at KEK. Two rings are being built in the TRISTAN tunnel, which will be intersected at the Tsukuba Interaction Region (IR). The BELLE detector is located at IR. A pair of superconducting magnets is installed symmetrically with respect to IR in order to focus and steer the beams.

Two quadrupole magnets (QCS) are being prepared to focus the beams, two solenoid coils are to shield the magnetic field of the solenoid coil of the detector, and 6 correction coils are to steer the beams. These magnets are to be energized by high-stability power supplies (P.S.s) to maintain a long-term magnetic field. This paper discusses the details concerning the P.S.s and their control.

1. System

These P.S.s are operated by computers via VME-ARCNET. They are also operating under a safety system. Each P.S. has a fast-stop mode and a slow-stop mode. When a quench in a magnet occurs, the exciting current must be quickly decayed. On the other hand, in some cases, the current must be decreased slowly based on the judgment of the cryogenic computer or the operators.

1-1 Current Setting

The exciting current is remotely set by computers through the VME-ARCNET. The VME-ARCNET is adopted instead of the CAMAC in TRISTAN; 16-bit digital signals are sent to a DAC (Digital to Analog converter) in the P.S. The output of the DAC is used as a current reference of the P.S.

The interface board in the P.S. communicates via ARCNET. A cable from each P.S. carries faults-status signals to an interface module in a VME crate, which is connected to the computer system.

1-2 Fast-Stop Interlock

Quench detection is based on measurements of the voltage among the ends and center tap of the coil. If a quench occurs, a differential voltage appears, and the quench is detected. As soon as the detector sends a trigger signal to the P.S., it must be quickly stopped.

1-3 Slow-Stop Interlock

The EX1000 computer which controls the cryogenic system can command the P.S.s to stop either quickly or slowly. In a different way, the P.S.s can be stopped slowly by pressing stop-buttons for rotary warning lights (Patlight).

2. Main P.S. for QCS Magnets

In the TRISTAN main ring, 4 pairs of superconducting quadrupoles (QCS) were used at each 4 colliding sections. The 4 P.S.s were fabricated. At KEKB, one of them has been improved to excite new QCS magnets. The KEKB QCS magnets are compact compared to the TRISTAN QCS magnets. The 2 QCS magnets are powered in series.

The QCS P.S. has a capability of 3500 A and 15 V. This P.S. consists of a converter and a quench-protection circuit. The converter consists of 12-pulse phase-controlled rectifies, a passive filter and an active filter. An SCR switch has been prepared to intercept the dc current in the case of any quench trouble.

In the KEKB operation, the QCS magnets will be excited by a current of 2913 A. We can therefore use the TRISTAN QCS P.S. with a few improvements.

2-1 Effects for a new load

The inductance of the load becomes 36.4 mH instead of 120 mH. The resistance of the cable remains at 1.5 $m\Omega$. Therefore, tuning for the new magnet may be required. A transfer-function block diagram of the closed-loop control in the P.S. is given in ref. 1. The system has two closed control loops. The minor auto-voltage regulation (AVR) loop is inside the auto-current regulation (ACR) loop.

Here, the terms of the passive filter and active filter are neglected because the frequency region between 0.01~1 Hz is discussed. The state equation is

$$\frac{d}{dt}x(t) = A\cdot x(t) + B\cdot u(t)$$

and

$$x(t) = \begin{bmatrix} I \\ V \\ w \end{bmatrix} \qquad A = \begin{bmatrix} -0.125 & 0.125 & 0 \\ 0 & -0.503 & 1 \\ 0 & 0 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ 90.0 \\ 54.5 \end{bmatrix}$$

$u = 0.875 \cdot U - 0.0025 \cdot I$,

where I is the output current, V the output voltage, and w the output voltage of the ACR. The output equation is

$$y(t) = C \cdot x(t)\ , \quad C = [1,0,0].$$

Using the *Padé* approximation, a discrete equation is obtained. The step response for the TRISTAN and KEKB has been examined. Although the inductance becomes small, the response becomes slow. However, it has no problem during KEKB operation, because KEKB is a storage ring without acceleration.

2-2 *Fast stop and Slow stop*

The fast stop of the QCS P.S. is triggered from one of 3 quench detectors. The SCR switch intercepts the dc current within 1 ms, and the energy stored in the magnets dissipates in stainless-steel resistors through the diodes.

In KEKB, the inductance (L_1) of QCS of the right side is 16.2 mH, and L_2 of the left side is 20.2 mH. In order to reduce the current in the neutral line, we changed resistor R_1 based on the condition $L_1/R_1 = L_2/R_2$. The resistors are 0.1 Ω and 0.125 Ω.

In the slow-stop mode, a counter IC (which connected to the DAC) counts down by 1 bit per clock pulse. The current decreases at a rate of about 10 A/s.

3. Auxiliary P.S. for the QCS-R magnet

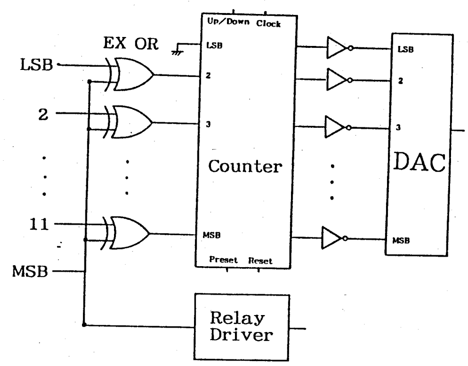
A bipolar 40 A auxiliary P.S. is connected to the QCS-R magnet. Such a connection produces an imbalance between two QCS magnets to zero with the required accuracy. On the contrary, it has the possibility to produce an imbalance of the field integrals between two magnets.

The output terminals of the auxiliary P.S. are connected to a magnet through contactors. The relay contactors are used to change the polarity on the magnet. The half voltage of the main P.S. imposes the output of the auxiliary P.S. To avoid this situation, a series of diodes is installed in line, which produces an offset voltage of 7 V.

The interface circuit is shown in Fig.1. The current of the bipolar P.S. is designed to be set by its complement. The polarity is set based on the value of the most significant bit (MSB); a "0" indicates positive polarity and a "1" indicates negative polarity. The circuit in Fig.1 separates 12 bits into a polarity bit and 11 bits of the absolute value.

The conversion process of the binary code is tabulated in Fig.1. One-bit multiplication is performed through the Exclusive OR gate. The connection between the Exclusive ORs and the counter ICs is shifted by one bit to the MSB. The least-significant bit (LSB) is "0". The counter is an up-down (reversible) counter. The counter can be preset to store binary numbers.

The current reference from the absolute circuit counts down by applying the slow-stop command. Then, the magnet excitation current decreases in proportion to the speed of the clock pulse.



	Computer Code	EXOR Output	Counter Output
+ Full	$[011111111111]_2$	$[011111111111]_2$	$[111111111110]_2$
+1	$[000000000001]_2$	$[000000000001]_2$	$[000000000010]_2$
0	$[000000000000]_2$	$[000000000000]_2$	$[000000000000]_2$
-1	$[111111111111]_2$	$[000000000000]_2$	$[000000000000]_2$
- Full	$[100000000000]_2$	$[011111111111]_2$	$[111111111111]_2$

Fig.1:Interface circuit

4. P.S.s for Solenoid Coils

The detector BELLE at IR has a solenoid field with 1.5 T to distinguish the particle track. The solenoid field couples the horizontal and vertical betatron oscillations of the beam. This makes a ring less dynamically stable and lowers the peak luminosity. The simplest compensation is to place two half-solenoids at each side of the IR.[2)]

Superconducting solenoid coils are installed before the first quadrupole QCS. The inductance of the right-side solenoid is 1.44 H, and that of the left side is 0.9 H. Since the resistances of the cabling from the P.S. to the magnet are 8.3 mΩ and 11 mΩ, the time constants are 173 s and 82 s, respectively.

4-1 *Switching Power Supply*

In KEKB, many switching P.S.s will be installed. R&D work for 20 kW switching P.S.s has been performed. We adopted these as the new P.S.s for the superconducting coils. The ratings of the solenoid P.S. are 650 A and 30 V.

The three-phase input (AC 420V) is rectified and filtered to provide an unregulated dc voltage (DC 600V). The DC-DC converter consists of 2 IGBTs, a PWM circuit to drive IGBT, 2 transformers and 4 rectifying diodes of 2 half-bridges. Unregulated dc is converted into high-frequency square waves by the IGBTs. The IGBT (insulated gate bipolar transistor) offers low on-state losses and simple FET-like gate requirements. The square waves through the high-frequency transformers are rectified. The output voltage of the DC-DC converter is controlled by the PWM (pulse width modulator) citcuit. The voltage is varied by changing the switching duty ratio, which is defined as the ratio of the on-duration to the switching time period. The switching frequency is 20 kHz, which is sufficiently more than 12 kHz, in order not to generate audio noises. The passive filter at the output of the rectifier consists of L-C filters and R-C damping branchs. The filters regulate a ripple within 1%.

Power FET as the controlling element is used. There are 88 paralleled FETs in the output stage operating with a collector voltage of 2 V. The FET regulator controls the final output voltage in accordance with the output of the current regulator. The FET operates in the linear mode. The current regulator obtains its feedback signal from a high-precision DCCT.

DANFYSIK 864I DCCT is adopted as a current-sensing transducer. This type DCCT is compact and cheap compared to the 4-core-type DCCT used in TRISTAN.[3)] The temperature drift is less than 0.1 $ppm/^{\circ}C$. The long-term stability is less than 1 ppm/month. The deviation from linearity is less than 10 ppm.

The output current must be compared with a current reference. The reference source is a 16-bit DAC on its 10 V dc scale. The error signal is sent to the FET bank and PMW controller to produce a pre-regulate voltage. The design requirement for this loop is a zero steady state error; hence, a PI regulator is used.

A temperature-regulated environment is created within the P.S. for the burden resistor of the DCCT, the DAC, and the current-error amplifier. This is accomplished on the same heat sink by cooling the above mentioned components with a Peltier device, whose temperature is regulated within $\pm 0.5^{\circ}C$ at 25 $^{\circ}C$. These components are mounted on a 11 cm long $\times$ 8 cm wide $\times$10 mm thick copper plate. An electronic Peltier module is soft soldered on the back of the plate.

The required specification for current regulation is less than 100 ppm/year, including long-term drift, under the various environmental perturbations. The input AC lines may vary by $\pm$ 10%. The ambient temperature during operation is assumed to be in the range between 10 $^{\circ}C$ and 50$^{\circ}C$.

4-2 *Fast-Stop and Slow-Stop*

In fast-stop, a DCCB intercepts the dc current. The response speed is less than 50 ms, which is much slower than the SCR switch because of opening the mechanical contactors. The operation is limited to 500 times. However, the cost is very cheap compared to that of the SCR switch. A damping resistor of 0.71 Ω is connected to the terminals through a diode. The voltage of 500V is produced in the quench.

In slow-stop, the gate pulses to fire IGBTs are blocked and the source voltage of the converter is vanished. The current through the magnet naturally decays with a time constant of some minutes.

5. P.S.s for Correction Coils

Correction coils (a skew quadrupole, an H-dipole and a V-dipole) are housed in each of the QCS cryostats. These 6 coils are excited by 6 bipolar P.S.s. The inductance of the skew is 23 mH, and that of the steering is 45 mH. The ratings of the P.S. are $\pm$50 A and $\pm$20 V.

AC 200V is rectified, switched by FETs and filtered to provide a low-level DC output. The switching frequency is 100 kHz. The dropper for the current control is 14 FETs in parallel. The terminals of the DC output are connected to the magnet though relay contactors. The relay contactors are used to change the polarity. An energy-damping circuit is installed between the relay contactors and the magnet. The current is monitored using two DCCTs (IT150-S (NIPPON LEM K.K.)). One is for current stabilization control and the other for the monitor.

In fast-stop, a DCCB intercepts the dc current. Since the energy damping resistor is 2Ω, the voltage across the resistor is limited to 100 V. In slow-stop, the P.S. is turned off. The current decreases within 1 s.

Summary

The QCS power supply is improved so as to excite the new load. Eight switching power supplies were fabricated. These will be used for measuring the magnetic field at IR from the autumn of 1997.

References

(1) T. Ozaki et al.: Proceeding of the 8th Symposium on Accelerator Science and Technology (1991) 232.

(2) "KEKB B-Factory Design Report", KEK Report 95-7 (1995).

(3) T. Ozaki: Proceeding of the 10th Symposium on Accelerator Science and Technology (1995) 106.