Power Supply System for Superconducting Quadrupole Magnets of the TRISTAN main ring

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Abstract

The excitation system for the superconducting quadrupole magnets of the TRISTAN main ring is composed of a 3500 A power supply, a 40 A auxiliary power supply and a quench protection circuit. In the quench, a DC switch separates the magnets from the power supply within one ms. The performance of the main power supply is described.

Introduction

In the TRISTAN main ring, a pair of high-gradient superconducting quadrupole magnets (QCS) has been installed quite close to the collision point to increase the luminosity [1,2]. The eight iron-free quadrupoles were designed for an operating field gradient of 70 T/m with a current of 3405A, and were trained up to 4000 A in the laboratory. The quadrupole has an effective magnet length of 1.14 m, and provides a good field aperture of 94 mm diameter. The magnets are cooled by the forced circulation of single-phase liquid helium at 4.5 K. The two magnets in the cryostats are electrically connected in series with superconduting cable. A power supply is connected to the current lead of the cryostats through four parallel normal power cables of 800 mm^2 cross-section, with a one way length of about 100 m. The four DC power supplies for the QCS are installed at ground level near each collision point.

Constitution of power supply

The power supply (P.S.) exciting the QCS magnets is composed of a quench protection circuit, a main P.S. and an auxiliary P.S. as shown in Fig.1.

Quench protection circuit

The quench protection circuit is composed of a DC current interrupting switch, energy dump resistors (R1,R2) and three quench detectors (Q.D.) as shown in Fig.1. The DC switch is
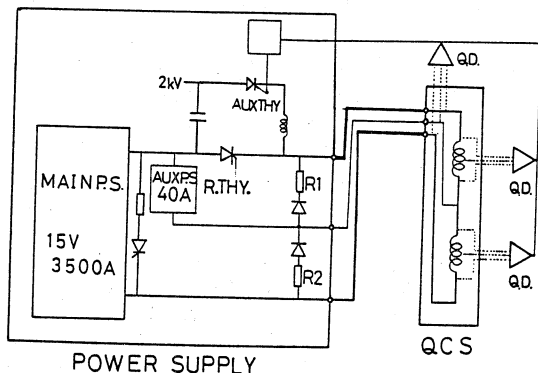

POWER SUPPLY

Fig.1   Constitution of power supply system.

installed between the power supplies and the superconducting magnet load. The DC switch consists of six reverse-conducting thyristors (Mitsubishi Denki Corp. : FR 1000BX-50), connected in parallel. The rating of each element is 2500V and 1000A. The switch operates as follows. In a quench, the auxiliary thyristor is triggered from the quench detector, and the capacitor discharges. The discharge current flows though reverse-conducting thyristors in the direction opposite to the main P.S. current. The thyristors turn off at the instant of zero current. The switching time is less than one ms. This high speed protection minimizes damage to the magnet. In addition, a crowbar thyristor is installed to protect the P.S. from any surge voltage.

The three quench detectors are connected to each quadrupole magnet and a superconducting bus line. Each quench detector uses a conventional center tap balance method, compares the induced voltages on the two halves of the coil and detects any balance voltage between them. The threshold for the unbalanced voltage is typically set at 1 V for 10 ms.

When a quench is detected, the power supply is separated from the magnet by opening the DC switch, discharging the stored energy in the magnet through two resistors with a time constant of 0.48 s. The energy damp resistors are made of stainless pipe with fins and are air-cooled. The resistance is 0.125 Ω

If this quench detector should fail to detect a quench, a sudden pressure rise in the helium vessel and temperature rise at the coil would then trigger the DC switch.

Data recorders are prepared at each local control room to record current and temperature of the magnet. The trigger signal to the data recorder is sent from the quench detector and the situation before and after the quench is recorded. The recorded signal is examined to determine the cause of the trouble.

Main power supply

A stabilized DC P.S. excites two magnets in series. The rated current and voltage are 3500 A and 15 V, respectively. The output voltage is somewhat lower, about 10 V, primarily due to the voltage drop across the 200 m long cable connecting the load and the power supply. The inductance of the load is 120 mH. The ramp-rate is typically 10 A/s.

The principal circuit is shown in Fig. 2. The main P.S. is a twelve-pulse bridge converter connected to the isolated delta-delta and wye-delta windings of a transformer. This connection of the transformers results in a fundamental ripple frequency of 1200 Hz. Thyristors are used to rectify and stabilize the output voltage by controlling the switching phases. The two thyristor bridges are connected in parallel by an interphase transformer.

Two stages of filtering are provided to reduce ripple and thyristor switching noise effectively. The first stage consists of a passive LC filter which is effective for the fundamental and the harmonic ripple. The second stage consists of an active filter which is comprised of a voltage divider, a DC amplifier and a transformer. The active filter is a feed-forward circuit as described below. The detected voltage ripple just after the passive filter is amplified in the DC amplifier, and the output is inversely added to the ripple through the transformer. The active filter reduces the ripple at 50 Hz which arises from the phase
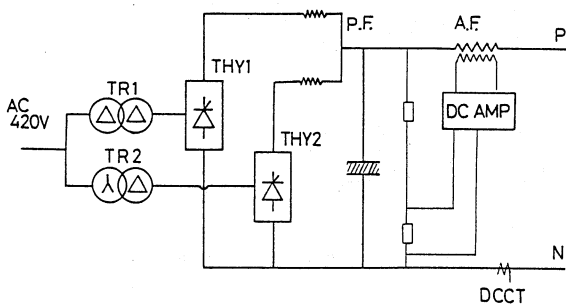
Fig.2 Principal circuit of main power supply.

Fig.3 Feedback control system of main power supply.

unbalance between the 3-phase AC lines and/or unbalanced firing timing of the thyristors.

A direct-current current transformer (DCCT) senses the output current and provides a linearity of better than $\pm 4 \times 10^{-6}$. The output voltage of DCCT is used for current detection in the current feedback loop. The excitation current is set by a digital to analog converter (DAC). The DAC-1136 (ANALOG DEVICES) is controlled at constant temperature so that the drift of the output is reduced to about ± 20 ppm. The reference current pattern is supplied as 16 bit digital data from a CAMAC memory module.

Auxiliary power supply

An auxiliary 40 A DC P.S. is provided to compensate the difference in the effective lengths of paired magnets. The effective length of the magnet is measured by means of rotating coils [3]. The magnet with shorter effective length is connected to the auxiliary P.S.. The correction current is added to the main current. The current pattern is supplied as 12 bit digital data from the another memory module.

interlock and control

The internal interlock of QCS P.S. is controlled by two programable controllers (HIZAC D-64) which are flexible and suitable for R&D work.

The external interlocks are the above described quench interlock and an excitation prohibition interlock. A mini-computer EX-1000 which controls the cryogenic system permits magnet excitation to the QCS P.S.. The P.S. is driven by HIDIC-80E mini-computer from TRISTAN central control room. In case of trouble, an operator or EX-1000 denies permission for the excitation , and the QCS P.S. stops in fast-mode or slow-mode.

Performance of main power supply

static performance

The measured ripple voltages were typically about 50 mV (rms) at 3500 A, corresponding to a 4 mA current ripple.

Measurements of stability verified current stability at 3500A to be better than 3×10^{-5} during 3-4 hour operation. The measurements were performed to compare the DCCT output voltage and the DC voltage standard (Fluke 335D).

dynamic response of power supply

The excitation current is set by digital data via a CAMAC module from the central control room. During beam acceleration, the demanded current value for magnet excitation ramps up, but the actual current deviates slightly because of the dynamic response of the P.S.. The electrical L/R time constant of the load (magnet and power cables) is about 20 s. This is much larger than that of the normal magnet (1 s). The P.S. requires a smooth current response to the reference current pattern, but the P.S
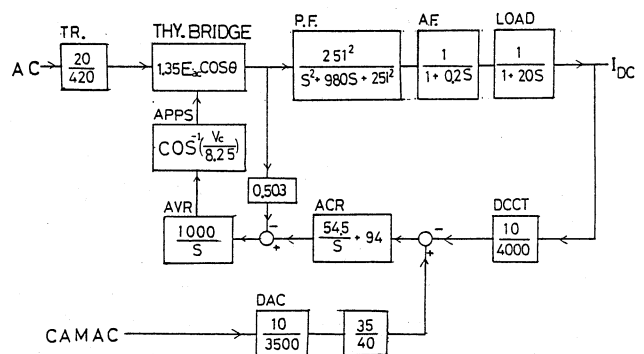
must be stable for any disturbance. In order to study these deviations, computer simulations were performed and the parameters of the feedback control system were optimized.

These feedback control simulations are based on the theory of the transfer function [4]. As seen in Fig.3, the control system consists of one minor-AVR (auto voltage regulator) loop and one ACR (auto current regulator) loop. The APPS (auto pulse phase shifter) is specified to be the arccosine of the AVR output. The characteristics of this system is analyzed on the assumption that the transfer functions describe the elements of the power supply precisely. The behavior of the system in the time domain is determined from the inverse Laplace transform.

The deviation of the output current behind the current reference commanded by the CAMAC was obtained by measuring the difference between the output of DAC and that of DCCT. The deviation value was 0.1 A with the ramp-rate of 9.4 A/s. The simulation shows that the deviation is 0.14 A. In addition, the ACR gain was changed and the response to a step input was measured. The agreement between the measured waveform and the simulation is good. The control system shown in Fig.3 provides a good model. The current deviation (or time lag of the QCS P.S.) can be corrected by modifying the pattern form of the current reference, but the correction was not performed.

At the start of beam acceleration, a gradual ramping pattern region is needed. In TRISTAN, the region lasts about 20 s to avoid synchro-betatron resonance beam instability. This ramping is gradual enough for the QCS P.S.. Gradual stopping is also needed.

Initial operation

Mini-beta operation using QCS commenced in February,1991. The magnets were excited to about 2470 A for 29 GeV colliding experiments. The compensation currents of the auxiliary P.S.s were 1.1A,1.6A,2.7A and 3.8A at each collision point. The P.S.s were operating very stably.

Machine tuning was delayed due to QC1 coil shorting, and a number of other difficulties [5]. Nevertheless by the end of spring a record luminosity of 1.9×10^{31} cm^{-2} s^{-1} was achieved.

Acknowledgements

References
(1) K.Endo et al.: Proc. of IEEE Part. Accel. Conf. (San Francisco, 1991);KEK Preprint 91-33
(2) K.Tsuchiya et al.: Proc. of 2nd European Parti. Accel. Conf. (Nice, 1990) ; KEK Preprint 90-124
(3) K.Egawa et al.: Proc. of IEEE Part. Accel. Conf. (San Francisco, 1991) ; KEK Preprint 91-52
(4) M.Takanaka and S.Watanabe: INS-T-456 (1986)
(5) S.Kamada and H.Fukuma: KEK Preprint 91-76